BRAIN

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ON SOME PRESSURE EFFECTS ASSOCIATED WITH CERVICAL AND WITH RUDIMENTARY AND "NORMAL" FIRST RIBS, AND THE FACTORS ENTERING INTO THEIR CAUSATION.

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I.—INTRODUCTION.

THE growth and state of our knowledge of the subject indicated in the title of this paper have been traced so often and in such detail in the very numerous anatomical and clinical papers dealing with it that there might seem little new to say thereon. In all the categories named, the morphological and ætiological factors involved appear relatively simple: the lesions in question have been studied by anatomists and exposed by surgeons on countless occasions, and it might be thought that the varieties of abnormal costal element, the full range of their clinical manifestations, and the correlation of these with the different bony anomalies, must by now be fully understood. Indeed, this was the sanguine view expressed by an anatomist, Wingate Todd, in 1912, when he wrote that "investigation into the condition known as 'cervical rib' has now elucidated the whole of the symptom complex and revealed in detail its causation." Yet, after the lapse of over thirty years, the briefest survey reveals that we are still far from any such satisfactory state of knowledge, and it may almost be said that we have scarcely yet envisaged the problems concerned in their fullness.

The background of rib pressure syndromes is more complex than Wingate Todd realized, though some important and relevant factors were revealed by his own studies. Variations in rib formation at the upper thoracic operculum are accompanied, and are thought to be in part produced, by variations in the segmental derivation of the brachial plexus, but the two variations do not always tally in degree. Thus, Wingate Todd (1911) pointed out that a cervical rib may co-exist with a brachial plexus that shows no signs of prefixation, and we know that the precise segmental origin of the motor and sensory innervation of the upper limb may vary by as much as an entire spinal cord segment. In the attempt to correlate a particular rib anomaly with the signs of disturbed nervous function that may accompany it, we are therefore dealing with two variables that bear no constant relationship to one another. Possibly, the case is simpler with a rudimentary first rib, since this seems always to be associated with post-fixation of the brachial plexus to which the whole of the first and a considerable quota from the second thoracic nerve root contribute (Herslet and Keith, 1895; Wood Jones, 1910; Dow, 1925).

In the case of the abnormal costal element, it is clear that we cannot always be certain of the accuracy of the label "cervical" as applied to it. Surgically, any abnormal rib in this situation is likely to be thus labelled, and this is as much the case now as when Wood Jones in 1913 stated that "rudimentary first ribs have been repeatedly met with and described as dissecting room curiosities . . . it seems certain that some forms of them would be capable of producing symptoms such as are produced by cervical ribs. Indeed, I believe that these cases by any ordinary methods of examination would be taken for, and regarded as, instances of cervical rib. Clinically, these aborted first ribs have received no recognition: yet many of them are recorded in anatomical literature, and it is extremely probable that under the general heading of 'cervical rib' many such cases are included in clinical records. . . . What remains for the radiographer to do in this inquiry is to determine, beyond any dispute, which member of the vertebral series gives origin to the rudimentary rib. Probably many interesting facts will come to light when this is done as an ordinary detail of routine. . . . Unfortunately, radiographers have relied on a very false criterion for determining vertebral levels in this region. It has been laid down as an axiom that the slope of the transverse process is diagnostic, for it is said that those of the seventh cervical are short and usually set at right angles with the vertebral column, or have a downward tendency, while the first dorsal processes are larger

and have an upward tendency. No reliance can be placed upon this slope of the transverse processes even in the normal skeleton, and in cases in which abnormal rib development is present it is a most misleading feature. Many of the published skiagrams which illustrate classical cases of cervical rib are, judged by this criterion, cases of rudimentary first dorsal rib. . . . It is only by counting the number of vertebræ which lie cephalic to the disputed member that the real nature of a costal element may be determined with certainty." Dow (1925) has made similar criticisms, but it is certain that the necessary radiographic precautions are not yet systematically taken. It is common to see skiagrams of suspected cervical rib in which the vertebral derivation is not revealed, and in which the full course of the cervical and first two thoracic ribs is not included on both sides. Yet in the presence of an abnormal first rib, the second rib is commonly altered, a fact that is of value in ascertaining the derivation of the abnormal element under suspicion.

Turner's (1883) early anatomical studies of abnormal first and second ribs show how easily, even in the dissecting room, and with the dried specimen, errors of identification may be made. More complete discussion, of this point will be given in a subsequent chapter.

Yet even when we have decided the place of an abnormal rib in the series, we are by no means at the end of the relevant associated bony anomalies which may be of clinical significance. Cervico-dorsal scoliosis is extremely common, and so also are deformations of the vertebræ in this region. Some of these deviations from the normal are described and pictured in Keen's paper (1907) and one or more of them were present in each of the personally observed cases here recorded. It might almost be said that an abnormal rib is never a solitary anatomical aberration, and *indeed it will be submitted in this paper that cases of abnormal rib associated with clinical symptoms should be primarily thought of, not in terms exclusively of the abnormal rib present but in terms of an abnormal upper thoracic outlet.* This outlet is invariably asymmetrical, commonly narrower on one side than on the other, and tilted to one side. This is the essential abnormality *from a clinical point of view*, and whether the abnormal rib in question is cervical or first thoracic is probably in most cases a matter of indifference.

This generalization clearly does not apply to one category of case to be considered here, namely, those in which pressure symptoms referable to nerves or artery are found in the presence of an apparently normal thoracic outlet: the cases described as examples of "normal first rib pressure" or of the "scalenus anticus syndrome." Here, as will appear,

the essential factor is an alteration in the normal topographical relationship of thoracic outlet to shoulder girdle, the latter having sagged owing to atonia of its supporting musculature.

Passing from the aberrations of brachial plexus derivation and of skeletal formation, we come next to consider the symptoms resulting from the maladjustments between bony structures on the one hand, and nerve roots and subclavian artery on the other. It can be said at once that we have not yet fully accounted for these symptoms, nervous or vascular, and in respect of the latter in particular there is considerable conflict of opinion and a serious dearth of systematic observation.

A wide range of vascular symptoms has been recorded in association with abnormal ribs at the upper thoracic outlet and various views have been advanced to account for them. The earlier view, fully expounded by Keen (1907), was that they are all to be accounted for by mechanical obstruction to the blood flow through the subclavian artery, either by stretching or angulation over the rib, or by thrombosis within the artery, or by all of these factors. In this country, this view has been largely superseded by the hypothesis that they all result from pressure on sympathetic fibres in the first thoracic nerve root, where this crosses, and is stretched by, the rib (Stopford and Telford, 1919, 1931; Wilson, 1940). Yet, clearly, this view cannot contain the whole truth of the matter, if indeed it contains any of it, for paralysis of sympathetic fibres can account neither for the instant obliteration of the radial pulse in many cases on traction on the dependent arm, or during its elevation, nor for the instant return of the pulse when the limb is released. Nor can it account for the permanent absence of the radial and of the brachial pulse in certain cases of rib pressure. Even the more commonly reported cyanosis, coldness, pallor and tingling of the hand cannot be accounted for on any hypothesis of sympathetic nerve fibre paralysis, for these symptoms fluctuate and intermit rapidly, being influenced by the posture of the limb and by the uses to which this is put. When somatic nerve fibres are compressed in the first thoracic root by an abnormal rib, the motor and sensory consequences of this pressure—wasting, weakness and sensory loss—do not fluctuate in this fashion, and, indeed, behaviour of this order is not compatible with structural damage to nerve fibres. In fact, these so-called vasomotor symptoms are conditioned by just those factors that lead to interference with the blood flow through the subclavian artery, while, finally, paralysis of the sympathetic nerve supply to the upper limb leads to vasodilatation with increased warmth and redness of the limb, and loss of sweating and pilomotor activity. How

in these circumstances we have come to invoke and to accept the untenable hypothesis of sympathetic paralysis or irritation in respect of pulselessness, coldness, pallor, coldness and tingling in the hand is difficult to understand. A comparable confusion surrounds the occasional occurrence of the syndrome of the stellate ganglion, or of its oculo-pupillary component (Horner's syndrome) in cases of abnormal rib, or of normal first rib pressure. This also is vaguely attributed either to pressure on the oculo-pupillary sympathetic fibres in the first thoracic nerve root, or to the involvement in some unexplained way of the cervical sympathetic chain, though, as will be seen, neither of these events can account for all the facts.

The production of symptoms in the presence of abnormal ribs involves yet another factor of not less importance, perhaps, than the bony anomaly itself, and this we may call the pathological factor. The consequences of any anatomical maladjustment between nerve roots, artery and bones are inevitably aggravated by the constant movement that goes on between the structures concerned. Thus, as has been pointed out, the thorax moves up and down some 23,000 times in the 24-hour period, while the use of the arm and the associated motion of the shoulder girdle lead to a still wider and more irregular range of disturbance in the relations of ribs, nerve roots and subclavian artery. That this is so is widely recognized, but what tends to escape attention is that the recurrent friction, compression and stretching of soft tissues may, if excessive, lead to considerable reactionary tissue change.

The neurologist is prone to think of his problems too exclusively in terms of disordered function and structure in nerve cells and fibres, and to neglect the grosser pathological phenomena: the general tissue reactions to damage, that may be associated with them and may even be of greater clinical significance. In the circumstances now under consideration we may expect to find damage to the walls of the subclavian artery, even to a degree capable of leading to the formation of aneurysmal dilatation and to thrombosis. We may expect also the development of inflammatory fibrous tissue around all the soft structures involved. In surgical accounts of findings at operation in cases of abnormal rib we do not get the information under this heading that we might reasonably hope to get, but there can be no doubt that changes of the order here referred to do occur. In a description of two cases of rudimentary first rib, studied in the dissecting room by Dow (1925), we read of a dense band of fibrous tissue covering and binding the subclavian artery down to the pleura, while in a graphic description of an operation upon a case

of cervical rib by Lewis and Pickering (1934) mention is made that the artery was fixed to the rib by dense fibrous tissue. A similar case is here reported. This fixation is not the only hazard to which the artery is exposed, and aneurysmal dilatation of the third part of the artery has been recorded on many occasions, sometimes with the complete or partial occlusion of the sac by clot resulting in severe ischæmic symptoms in the limb. These changes are themselves, therefore, productive of pathological manifestations and add their quota to the sum total of signs and symptoms in a case of abnormal rib.

What stands out clearly, therefore, from this brief summary is the presence of a multiplicity of factors in every case of rib pressure syndrome, and the customary clinical diagnosis of cervical or of rudimentary first rib is apt to give rise to an unreal and artificially simplified conception of the problem at issue. The title "scalenus anticus syndrome" is a comparable example of an even more naive conception of the processes involved in the syndrome so named.

Turning now to a brief preliminary consideration of the clinical literature, we find that cases presenting pressure symptoms in nerve roots or subclavian artery are commonly grouped under the headings of cervical rib, rudimentary first rib, and normal first rib or scalenus anticus syndromes. On cervical rib there is an abundant literature, but that on rudimentary first rib is extremely scanty. More attention has been paid to pressure symptoms in association with "normal" first ribs (Bramwell, 1903; Bramwell and Dykes, 1921), but of late years this has given place to descriptions of what is called the scalenus anticus syndrome. It will be submitted in this paper that there are really only two categories in question: (i) those associated with an abnormal upper thoracic outlet, and (ii) those with a normal thoracic outlet, but with an altered topographical relationship between this and the shoulder girdle. The first category includes cases of cervical and rudimentary first rib, the second those known as "normal first rib" and "scalenus anticus" syndromes.

It should now be clear enough that a number of questions remain for solution in respect of both categories. We do not know, for example, whether it is clinically possible to distinguish cervical from rudimentary first rib syndromes: whether vascular symptoms are more often associated with one of these bony anomalies than with the other: why in some cases nervous, and in others, vascular symptoms predominate or occur alone. We are not generally agreed as to the full range of vascular symptoms, or as to the factors responsible for their appearance: we do

not know the precise character and incidence of sympathetic symptoms, or the seat of the lesion involving the sympathetic system when symptoms referable to it are present: and finally we are not generally agreed as to the factors operating in cases of "rib pressure syndrome" where no abnormal costal element is present.

It is possible that in the present state of knowledge not all the questions raised in this way can be answered, and that their satisfactory solution must await a more thorough clinical and radiographical study than we have yet given to them. In the meantime, it may serve to direct attention to the subject if a small series of personally observed cases are described and discussed in the light of the considerations outlined in this introductory chapter.

II.—Clinical.

As must often have happened in clinical medicine, it was the study of a particular and unusual case, one of rudimentary first rib, that first forced these problems upon the attention of the present writers, and a description of this case opens the series.

Case 1.—Right rudimentary first rib: vascular and sympathetic symptoms. The patient was a medical practitioner, aged 37, who as a younger man had suffered no physical disability. He had, in fact, been a keen tennis and fives player and had represented his university at the former game. In August 1942 he had to undergo a fortnight's physical training course of some severity. He had to carry a heavy man on his back and to bear loaded stretchers over a rough and arduous course. The episode which precipitated the sudden development of symptoms occurred on an occasion when he was engaged in the latter occupation. His companion stretcher-bearer collapsed and a suddenly increased strain was thus thrown upon the patient's arms. During the ensuing days he developed the following sequence of symptoms: an extremely painful stiff neck with congestion of the right conjunctiva and nasal mucosa. Rapidly recurring attacks of painful stiff neck and a steadily increasing bruit, synchronous with the heart beat, appeared. This was heard not only by himself but also by his wife as she sat beside him.

In January 1943 the pain and stiffness of the neck were so severe that he had a course of massage. The congestion of the right conjunctiva and of the nasal mucosa on the right side recurred constantly, and was always worse during the night, so that for very many weeks he could sleep comfortably only when sitting up. In March of that year, following an afternoon's tennis, intense pain developed in the right side of the head and neck with stiffness of the neck. He noted that his right palpebral fissure was narrowed and the right pupil smaller than the left. He was at once admitted to hospital as a suspected case of subarachnoid hæmorrhage, but lumbar puncture yielded a clear, colourless cerebrospinal fluid. The bruit was now at its height, the right conjunctiva and nasal mucosa very congested, and he developed an intense migrainous headache. He noted also an absence of sweating over the right face, neck, forequarter and upper limb. During his stay in hospital no neurological signs other than a right

Horner's syndrome and loss of sweating on the right side of the face were noted by his doctors, but it was thought that the ear drums, especially the left, were congested, and the right temporal artery dilated. The bruit was variable and on different occasions was heard on right and left sides of the head. The notes do not record whether its presence was sought outside the skull. The final diagnosis, therefore, was based on the stethoscopic findings alone and took no account of the sympathetic disturbances, the only neurological signs present. The abnormal rib was not thought to be relevant to this illness. The pain in head and neck persisted for some three weeks, gradually abating. During the ensuing weeks all the symptoms slowly cleared up, the drooping of the right eyelid became less, some sweating appeared where it had previously been lacking, and the bruit lessened, to disappear finally during the summer of 1943. But for several months, blocking of the right nostril by a swollen mucosa made sleeping in the supine position uncomfortable. Recurrent redness of the right conjunctiva recurred, and still does so after lying down. Any forceful use of the right arm, or the carrying of one of his children "pick-a-back" leads to pain and stiffness in the neck. He left hospital with a diagnosis of intracranial arteriovenous angioma and was finally invalided from the Service with this diagnosis. In addition to the foregoing symptoms, he now notices that the right hand readily gets cold and that there is occasionally some tingling on the mesial aspect of the right forearm and hand. At no time has there been weakness of the right upper limb.

Both his parents, and the patient himself up to about the age of 30, had recurrent migraine.

Examination in July, 1944, some two years after the onset of symptoms, revealed the following physical signs.

The right shoulder is noticeably lower than the left, and the line of the right clavicle nearer the horizontal, when traced from the middle-line outwards, than is that of the left. There is no visible swelling, but palpation reveals a hard, immobile mass immediately above the upper border of the right clavicle and one inch lateral to its sternal extremity. This can be traced upwards and slightly towards the middle line. Some distance along this mass can be felt a pulsating vessel passing from above downwards and outwards. There is no thrill, and auscultation now reveals no bruit in neck or head. The right hand is normal in colour, but notably drier than the left, which is sweating moderately. The pulses are equal and normal at both wrists, but traction on the hanging arm completely obliterates it at the right wrist, but has no effect upon that at the left. It also evokes some paræsthesiæ along the ulnar border of the right forearm and hand, but not along that of the left. There is no visible disparity between the right and left temporal arteries, though that on the right is the more tortuous. The heart presents no abnormality.

Nervous system.—Optic discs and vessels in fundi are normal on both sides. The right pupil is somewhat smaller than the left and the right palpebral fissure somewhat narrower than its fellow. There is no conjunctival or nasal mucosal congestion on the right, nor inequality of colour, warmth or of sweating on the two sides of the face. Ocular movements and the remaining cranial nerves are normal.

There is no disparity of any kind between the two upper limbs, and no weakness, wasting or sensory change in the right arm. The various arm-jerks are equal and normal on the two sides. Examination of the rest of the body reveals no abnormal neurological signs.

The skiagram (Dr. Cochrane Shanks) reveals the presence of a long rudimentary first thoracic rib on the right side (fig. 1). Turning abruptly forwards lateral to its costo-transverse articulation, this runs downwards, forwards and outwards to

join a large exostosis on the mesial border of the second rib. It terminates in an irregular tip immediately anterior to this junction and appears to be joined to a first costal cartilage by a thin strand of tissue (? ossified, ? fibrous) which runs forwards in the line of the bony part of the rib. The second rib can be clearly seen to join its own second costal cartilage lower down in the skiagram. The left first rib is normal. There are no cervical ribs. It can be seen that the rudimentary rib narrows the upper operculum of the thorax from side to side, and slightly raises its outer margin on the right side. The right clavicle lies lower at its lateral extremity than does the left, and it is apparent that the right shoulder lies at a lower level than the left.

Commentary.—Amongst the noteworthy features of the case are the role of trauma in precipitating symptoms, the dominance of vascular symptoms and the presence of sympathetic symptoms referable to a lesion of the stellate ganglion. Of the vascular symptoms, bruit seems to have been the most striking. No record exists in the literature of the audibility of a bruit in a case of rib pressure on auscultation of the skull. Indeed, it may be doubted whether investigation has ever been directed to this end. In the present case the initial diagnosis of intracranial vascular malformation probably led to auscultation of the head, and thus to a diagnostic inference that lacked neurological evidence. Keen (loc. cit.) and Sargent (1921) in referring to the bruit that may be present in cases of cervical rib, in the supraclavicular region, record that this is not propagated down the limb, but say nothing of its transmission upwards. The point is one that calls for more systematic study in future.

Whether in this case a relative stenosis of the artery as it crossed the rib or an abnormal dilatation distal to this crossing was in question cannot be determined, nor have we any information as to whether when the bruit was at its height there was a palpable thrill over the artery.

The disappearance of the vascular symptoms is capable of more than one explanation. A probable factor was the rise of the shoulder girdle upon the cessation of heavy use of the arm. It is possible, also, that the initial trauma led to the formation of a true or false aneurysm, in the manner to be discussed later, and to the subsequent formation of clot within it, though the presence, at this date, of a normal radial pulse rules out any degree of occlusion of the original arterial lumen. Further discussion of these symptoms will be deferred to a subsequent chapter.

The sympathetic symptoms in this case are of considerable interest. They indicate the stellate ganglion as the seat of the disorder of function. The oculo-pupillary component of this syndrome (Horner's syndrome) has been reported by several observers in cases diagnosed as due to

cervical, rudimentary and normal first ribs, as well as to the action of scalenus anticus (Keen, 1907; Puusepp, 1931; Sargent, 1921; Naffziger and Grant, 1938). Of the other components of the complete syndrome of paralysis of this ganglion, we find no mention in the literature nor any indication that their presence or absence was sought by the appropriate investigations. These symptoms are vasodilatation of skin of face, neck, forequarter and upper limb, together with loss of sweating and of pilomotor activity over the same region. In so far as any explanation has been attempted of Horner's syndrome, it seems to have been vaguely ascribed to pressure on sympathetic fibres in the first thoracic root where this crosses the rib, while by those who describe the scalenus anticus syndrome no attempt is made to account for it though this muscle clearly cannot have anything to do with its appearance. A brief summary of the relevant facts, anatomical and physiological, will show that rib pressure on the first thoracic root cannot play any part in its production, nor in that of the coldness, cyanosis, pallor and tingling of the fingers and hand seen in some cases of rib pressure.

The preganglionic oculo-pupillary fibres leave the spinal cord by the first and second thoracic nerve roots, and just beyond the emergence of these roots from the intervertebral foramina they pass into the white rami, which join the thoracic sympathetic chain. They travel thence by the stellate ganglion and cervical sympathetic chain, and their further course does not at present interest us. It may be emphasized, however, that they are not present in the root where this lies upon the rib.

Vasomotor, pilomotor and sudomotor fibres to the head and neck leave the spinal cord by the second, third and fourth thoracic nerve roots, enter white rami and join the thoracic sympathetic chain, thereafter following the same course as the oculopupillary fibres through the cervical sympathetic chain.

Vasomotor, pilomotor and sudomotor fibres for the upper limb leave the cord by the fourth to the tenth thoracic nerve roots, emerge from these as white rami to join the thoracic chain and to travel therein to the stellate ganglion. Here the pathway is taken over by postganglionic fibres, which pass as grey rami to the eighth cervical and first thoracic nerve roots close to the intervertebral foramina. These alone are the sympathetic fibres capable of being compressed by a rib.

The vertebral plexus consists of fibres which, leaving the stellate ganglion, run upwards round the vertebral artery. They enter the skull and innervate intracranial arteries.

It follows that the only situation in which the sympathetic fibres to head, neck, forequarter and upper limb are gathered together and capable of simultaneous involvement by a single lesion is the stellate ganglion, i.e. the fused inferior cervical and first thoracic ganglia. This structure lies immediately anterior to the head and neck of the first rib, or slightly lower than this, and in the lateral angle between subclavian and vertebral arteries. The ganglion has a further relation to the former of

these two arteries, for the annulus of Vieussens which arises in the ganglion encircles this artery, and, as it were, tethers subclavian artery and ganglion together. There is no such topographical relationship between the ganglion, a cervical rib or scalenus anticus. Precisely what factors lead to involvement of the ganglion in these circumstances cannot be stated. Possibly, traction on the artery and its displacement may lead

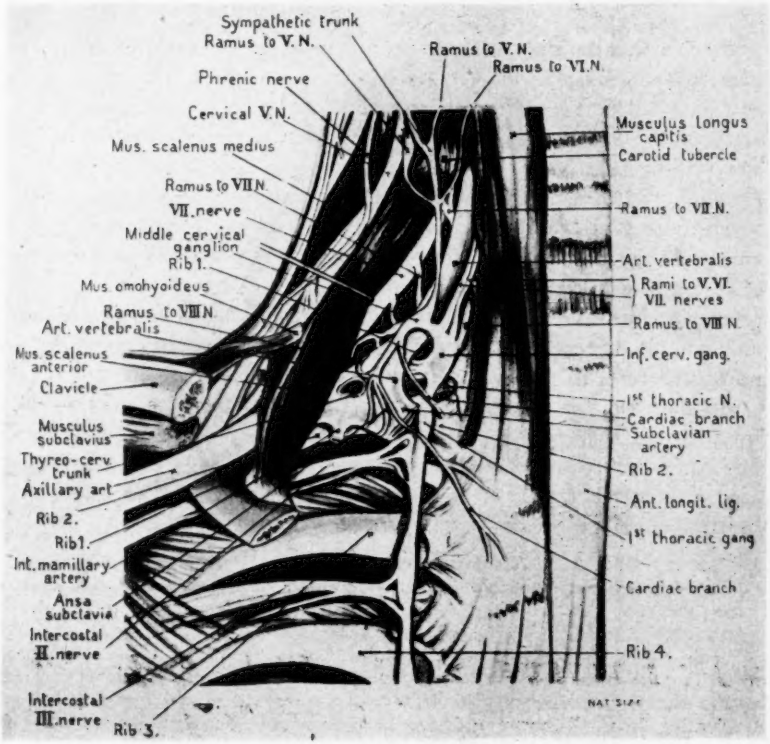

FIG. 2.—Connections of the sympathetic nerves at the root of the neck. From H. K. Potts, *Journ. Anat.*, 1925, **59**, 129. ⅔ nat. size.

to traction on the ganglion: possibly displacement of the first rib at the moment of trauma may have led to compression of the ganglion, or possibly, the latter may have become involved in an inflammatory tissue reaction, of the kind known (Dow, 1925; Lewis and Pickering, 1934) to be set up in the presence of an abnormal rib with maladjustment between

thoracic outlet and soft tissues. For reasons given earlier, it is clear that compression of sympathetic fibres in the first thoracic root, where this crosses the rib, affords no explanation of this sympathetic syndrome, nor can any action of scalenus anticus be invoked.

The anatomical facts relevant to the interpretation of true and of so-called sympathetic components of rib pressure syndromes are clearly illustrated in fig. 2, taken from Potts' article in the *Journal of Anatomy* (1925).

One further item in the syndrome in this case calls for brief comment: namely, the intense headache and stiffness of the neck, the sudden onset of which led, not unnaturally, to the suspicion that the case might be one of subarachnoid hæmorrhage or of intracranial arteriovenous angioma. The fibres which form the vertebral nerve or plexus arise in the stellate ganglion and pass into the skull along the artery of this name to innervate intracranial arteries, and it would be in accord with certain current views on the sympathetic factors concerned in the production of migrainous headache to suggest that a sudden lesion of this plexus at its point of origin may have played a principal role in this attack of headache and pain in the neck. The possibility of traction upon muscular and other structures in the neck cannot, of course, be excluded.

In the case just described, the onset of symptoms was clearly due to trauma, and these symptoms were vascular and sympathetic, there being no involvement of nerve roots in the brachial plexus. The following case represents another type of vascular syndrome, this time associated with indications of nerve root pressure.

Case 2.—Bilateral rudimentary first ribs: vascular symptoms predominant.—C. G., an unmarried domestic servant of 36, admitted to the National Hospital under the care of Dr. Purdon Martin on 16.6.42. About four weeks prior to admission she suddenly developed pain, redness and the appearances of a chilblain on the ulnar border of the left palm. In the course of ten days the pain spread to the thenar eminence, up the forearm and the outer side of the arm to the shoulder, and also into the scapular region. The pain was severe and lancinating. It usually came on during sleep and awoke her, keeping her awake for the rest of the night. When the pain was present, the whole hand tingled, felt cold and became blue in colour, and felt "as heavy as lead." Her only other symptom was a bilateral deafness of some 20 years' duration and due to otosclerosis.

On examination.—The optic discs and pupils were normal. There was no Horner's syndrome and no inequality of sweating on the two sides of the face. All movements of the left upper limb, especially of the distal segments, were very weak, and voluntary and passive movements of the limb evoked aching pain in the regions already mentioned. There was some wasting of hypothenar and thenar muscles and, doubtfully, of the interossei. No objective sensory impairment could be detected and the arm-jerks were normal and equal on the two sides. The left radial artery at the wrist and the brachial artery at elbow and

axilla were completely pulseless. The left arm and hand were colder than the right and were slightly cyanosed and sweating. When raised above the head, the limb blanched. The blood-pressure taken on the right arm was 140/80, but no

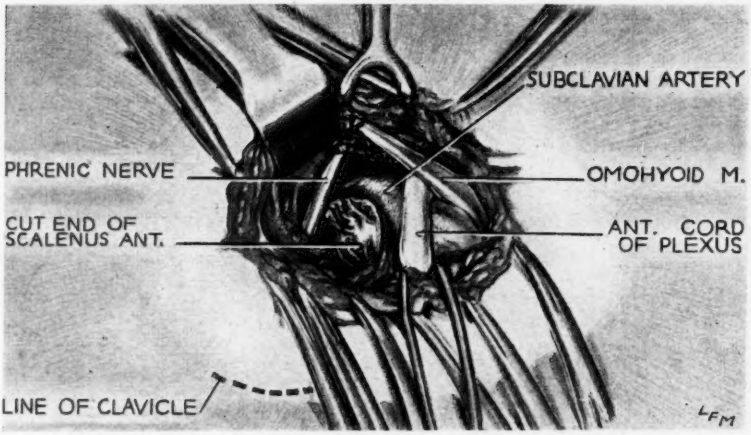

FIG. 4 *a*.

FIG. 4 *b*.

FIG. 4. (*Case 2*).—(*a*) Drawn from a sketch taken at operation, and showing the aneurysmal dilatation of the subclavian artery. (*b*) Photograph of the excised aneurysm.

pressure could be registered on the left. Above the left clavicle in the supra-clavicular triangle could be felt a firm elastic mass, about an inch in diameter.

Superficially it seemed movable, but its deep extension was immobile. It was not pulsatile. The normal pulsation of the subclavian artery on this side was only feebly felt. Pressure on this mass produced severe pain over the regions in which spontaneous pain was felt. Examination of blood and cerebrospinal fluid revealed no abnormalities. A skiagram revealed a pair of abnormal first thoracic ribs, the left one bearing an osteoma (fig. 3).

Dr. Cochrane Shanks has reported on this as follows: "There is a congenital deformity of the upper dorsal ribs. *On the left side* the head of the first rib, instead of articulating with the body of the first dorsal vertebra, articulates with both it and that of the seventh cervical. Its costo-transverse articulation is with the seventh cervical and it terminates by fusing with the middle of the rib below it. The second rib on this side is very flat below the point of fusion and repre-

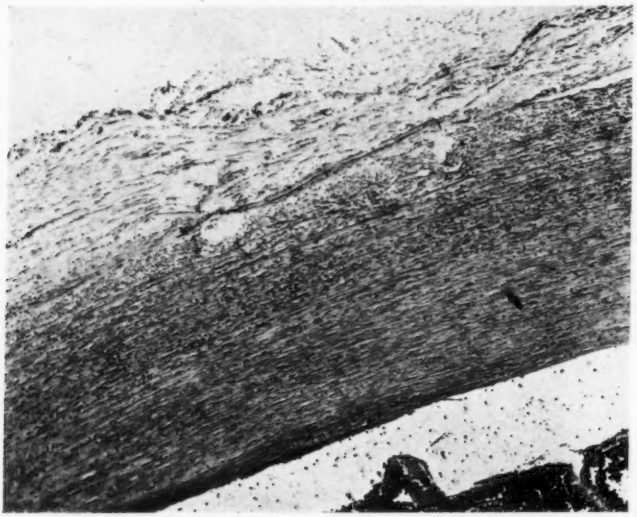

FIG. 5 (*Case 2*).—Photomicrograph of wall of excised portion of subclavian artery, showing clot in lumen and cellular infiltration of arterial wall.

sents anteriorly two ribs fused into one. The head of the second rib articulates with the body of the first dorsal vertebra. *On the right side* the uppermost rib is more completely developed and although it articulates posteriorly with the seventh cervical vertebra, it ends fairly normally by articulating through the costal cartilage with the manubrium sternæ. It has the characteristics of a cervical rib posteriorly and a true first rib anteriorly. The second rib on this side likewise articulates with the first dorsal vertebra behind and behaves as a second rib anteriorly.

It is as though the first ribs had attempted to become cervical ribs, with considerable success on the left side and only slight success on the right; and the second ribs on both sides show a similar upward morphological shift posteriorly."

Operation.—Mr. Harvey Jackson. A transverse incision was made above the left clavicle. The phrenic nerve and scalenus anticus were retracted medially and the

subclavian artery exposed. The artery was seen to be about twice its normal calibre, non-pulsatile and pushed forwards by a bony prominence lying behind it. This prominence arose from the first rib, growing upwards from its posterior part. Some of this bone was nibbled away with forceps, but it was found impossible to reduce the displacement of the artery completely by this means. A small extension of the incision was therefore made and the clavicle sawn through, exposing the artery more distally. The enlargement of the artery was then seen to be localized, it being of normal calibre distal to the enlargement. The enlarged portion was ligatured at each end and was then excised. It was three inches in length and filled with blood clot. The clavicle was then united by sutures and the wound closed (fig. 4 *a* and *b*).

The circulation in the arm and the general nutrition of the hand improved considerably following operation and there was satisfactory relief from pain. The muscular wasting gradually cleared up. Section of the vessel wall showed the muscular coat to be infiltrated by lymphocytes, and the lumen to be filled by clot (fig. 5).

Commentary.—The vascular symptoms in this case belong to a different category from those present in Case 1. In the latter the subclavian artery remained patent, even though it may have been stenosed as it crossed the rib, and it is possible that the dilatation so frequently described as occurring in the artery immediately distal to its passage over the first rib may have been present. In the absence of operative exploration no conclusion on this point can be reached. In Case 2, on the other hand, we are dealing with an aneurysmal sac involving subclavian and axillary arteries which had been occluded by clot. There was thus neither bruit nor thrill at the period the patient was under observation, but instead marked signs of grossly impaired circulation in the limb. To what extent the general weakness of the arm and hand was due to ischæmia, it is hard to say, but in addition to this factor there is clear evidence of pressure on either the first thoracic nerve root, or on the trunk formed by the union of this root with the eighth cervical. This evidence was provided by the local wasting of the hand muscles.

This case, therefore, may be said to have presented a complete nervous and vascular syndrome, there being no sympathetic component. The nature of the changes in the subclavian artery will be further discussed in a later chapter.

Case 3.—Right cervical rib: vascular symptoms, ischæmia and embolism.—W. E., a married woman of 38. She complained of pain in the right hand and arm of seven months' duration. For the past six to eight weeks there had been gangrene of the tips of the index and little fingers. The pain varied in intensity and extended from finger tips to elbow. The fingers felt cold and numbed, being at times reddish, at other times blue or white. On the whole the hand tended to be warm when she was erect, becoming cold and pale when she lay down. Pain was increased by immersing the hand in warm water.

On examination.—There is a definite swelling on the right side of the neck,

FIG. 1.—Skiagram of Case 1, showing rudimentary right first rib and drooping of right shoulder girdle as revealed by the line of the clavicle.

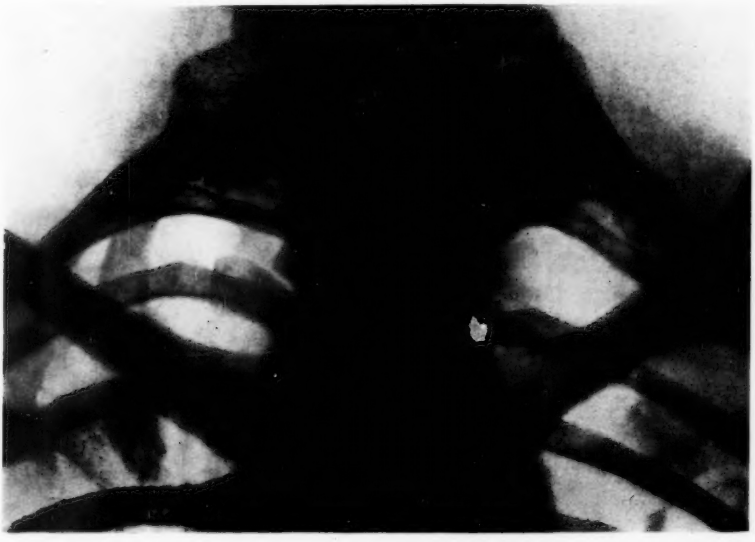

FIG. 3.—Skiagram of Case 2. Description in text.

To illustrate article by F. M. R. Walshe, Harvey Jackson and R. Wyburn-Mason.

immediately above the clavicle and lateral to the sternomastoid muscle. There is no pulse at the right wrist, and blood-pressure in the left arm is 150/80 mm.Hg. There is dry gangrene of the tips of the index and little fingers. The nails are brittle and show longitudinal streaks. There is hypalgesia and tactile hypæsthesia over the whole hand. There is no local wasting or weakness of hand or forearm muscles. Neurological and general examination reveal no other abnormalities. W.R. negative.

The skiagram reveals a right cervical rib fusing anteriorly with an exostosis on the first rib. Both first ribs in their anterior halves show an abnormal broadness, the transverse processes of the seventh cervical vertebræ are asymmetrical, the right pointing downwards and the left upwards, and as a result of the last-named anomaly the left first rib lies at a slightly higher level than the right (fig. 6).

Operation (Mr. Harvey Jackson, 14.8.41).—Through a curvilinear supraclavicular incision. The scalenus anticus seen to be constricting the subclavian artery, and when this muscle was divided it revealed a constriction of the artery behind the tendon with marked dilatation of the distal (third) part of the artery. A network of small veins surrounded the artery which was firmly bound down to the rib by fibrous tissue. On palpation the artery was firm and non-pulsatile, but after incision of the fibrous sheath pulsation in the artery could be felt. The junction of the anterior end of the cervical with the first rib was found to be the site of a prominence, amounting to an exostosis, this protrusion increasing the displacement and deformation of the artery. Removal of the bony prominence and of part of the cervical rib released the artery.

On the day following the operation, embolic foci were evident on the thenar eminence and middle finger, thus proving the patency of the artery distal to the site of operative exposure.

Owing to the slowness with which separation ensued and to the persistence of pain in the fingers, the terminal phalanges of the gangrenous digits were later removed. Ten days after the first operation pulsation could be felt at the wrist.

Commentary.—In this case of cervical rib, the symptomatology was wholly vascular. The arterial lesion was an aneurysmal dilatation of the third part of the subclavian artery, with clot formation. Embolism to the digital arteries had occurred before operation, but surgical intervention led to the separation of further embolic fragments of clot.

Case 4.—Abnormal first ribs : vascular symptoms.—W. B., a married woman of 42, with three children, the youngest 13 years. In her last two pregnancies she is said to have had "kidney trouble and high blood-pressure." Twelve years ago, and again eight months ago, she was admitted to hospital for "blood transfusions for anæmia," but no information is available as to her blood state at these times. For the past four years she has noticed that her hands and fingers "go dead" in cold weather, after domestic work, or after carrying her shopping basket. In these circumstances, the fingers begin to tingle, and then go yellow as though she had whitlows on them. The hand and fingers then become "stiff and clumsy," so that she cannot handle small objects or pick coins out of her purse. When "life begins to return to the fingers," they turn a bluish colour and feel as though the sinews in them were being pulled tight. On recovery, there are no residual paræsthesiæ and no disability. At times there is pain referred to the left shoulder region.

On examination.—She proves to be a very thin and sallow-complexioned woman, generally asthenic and weighing only 6 st. 8 lb. Blood-pressure is 125/90. As

FIG. 8 (*Case 5*).—Lateral view of fused cervical vertebræ. Klippel-Feil syndrome.

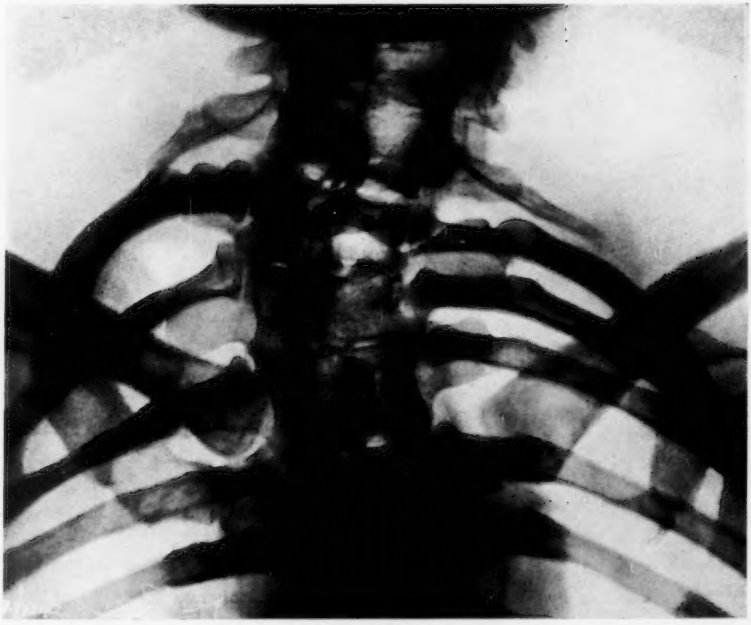

FIG. 9 (*Case 5*).—Cervical and upper dorsal spine, showing fusion of cervical vertebræ, articulated cervical ribs and scoliosis.

To illustrate article by F. M. R. Walshe, Harvey Jackson and R. Wyburn-Mason.

PLATE IV.

FIG. 6 (*Case 3*).—Right cervical rib fusing anteriorly with an exostosis on the first rib.

FIG. 7 (*Case 4*).—Showing abnormal first ribs and abnormal left second rib. See description in text.

To illustrate article by F. M. R. Walshe, Harvey Jackson and R. Wyburn-Mason.

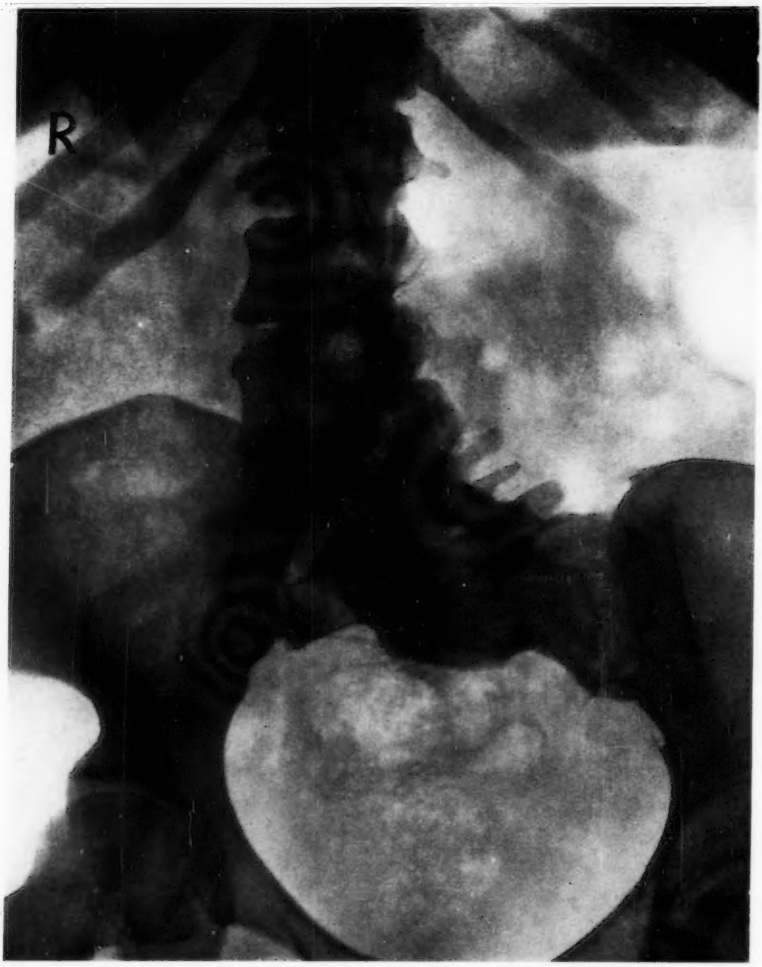

FIG. 10 (*Case 5*).—Showing lumbar and sacral spine.

To illustrate article by F. M. R. Walshe, Harvey Jackson and R. Wyburn-Mason.

she stands or lies supine both radial pulses are equal and of fair volume, but if her arms are elevated and pushed behind the vertical, the pulse disappears at both wrists. At present the hands and digits show no vascular abnormality, and there are no trophic changes in nails or skin. The subclavian arteries pulsate markedly above the clavicles, and upon several occasions a bruit was heard over them. A hard bony mass can be felt in each posterior triangle of the neck, larger on the left side. The skiagram shows a right first rib that is not normal in form anteriorly, for immediately in front of the scalene tubercle it appears to end as a bony structure, its junction with its cartilage being presumably fibrous. The left first rib is even more abnormal, and ends in contact with the second rib. It lacks the massive build and form of a normal first rib, and anterior to its junction with the second rib, the latter assumes the broad flattened form of a first rib. The thoracic outlet is markedly asymmetrical (fig. 7).

Commentary.—This case represents a common vascular type of rib pressure syndrome, occurring in a debilitated and atonic subject, the abnormal costal elements being first thoracic.

The last case of the series has no clinical aspect in respect of rib pressure symptoms, and therefore does not properly belong to this series of cases, but is described as exemplifying the wide range of skeletal and other malformations that may accompany an abnormal costal element at the upper thoracic outlet.

Case 5.—Cervical ribs, scoliosis, Klippel-Feil syndrome, fusion of some dorsal, lumbar and sacral vertebræ, with abnormalities in heart and lung. Death from rupture of cerebral aneurysm with subarachnoid hæmorrhage.—M. P., a woman of 34 years. Four years before admission she had had a subarachnoid hæmorrhage from which she had recovered with a slight right residual hemiparesis. Since that time she had complained of recurrent accesses of giddiness.

On examination.—She was seen to be a small woman of 4 ft. 4 in. height. The skull and face were asymmetrical, the right eyebrow and right nipple being placed higher than these same structures on the left side. Sternomastoid and trapezius muscles were virtually absent on both sides. The shoulders were abnormally high, the neck short and with a grossly limited range of movement in all directions. There was a double Sprengel deformity and marked kyphosis and scoliosis. There was clinical and radiographical evidence of patent interventricular septum.

Radiographical examination (Dr. Hugh Davies) showed an asymmetrical skull, the basi-occiput being elevated. No marked platybasia. The second to fifth cervical vertebræ showed fusion of the bodies and partial fusion of their laminæ, with only three spinous processes. There was a pair of articulated cervical ribs. There were twelve dorsal vertebræ, the second being incompletely developed, producing scoliosis. The bodies of the 3rd, 4th, and 5th were fused. There are three lumbar vertebræ, the remaining two of this series being fused with the sacral mass, which is oblique and sharply angulated forwards.

The patient died three years later from a second subarachnoid hæmorrhage when the clinical diagnosis and radiographic findings were verified at autopsy and a ruptured aneurysm on the left middle cerebral artery found.

In four of this small series of cases, the symptomatology has been predominantly vascular. They are of interest as exemplifying the

first with a second rib, and forwards from this fusion the combined rib is often abnormally broad, partaking, as it were, in the characters of both first and second ribs (fig. 7). It should be remembered, therefore, that a rudimentary first rib commonly implies the presence of an abnormal second rib, a feature seen in two of the cases here recorded. The fusion commonly occurs at what appears like an exostosis on the second rib, but in Case 4 here described, no actual fusion or exostosis was found. What is probably a case of bicipital rib is pictured in Keen's paper, the illustration being taken from an earlier paper by Weissenstein and reported as one of cervical rib. It is also interesting to record that in that classic work, Hilton's "Lectures on Rest and Pain," there is a brief account of a case in which an exostosis on what was believed to be the first rib produced obliteration of the subclavian artery with gangrene of the two ulnar fingers, and also pressure upon "the ulnar nerve" as the nerve trunk so named by the author crossed the exostosis.

In general, it seems that rudimentary first ribs are apt to be longer than cervical ribs and to be associated with a greater deviation from normal of the upper thoracic outlet, and to be more often accompanied by signs and symptoms referable to the subclavian artery.

The various forms of cervical rib have been described so often and in such detail (Sargent, 1921, and others) that further reference to them here is unnecessary, and all that need be said is that these accounts all suffer from a too exclusive pre-occupation with the rib itself and pay too little attention to the associated bony anomalies, for, indeed, we have not finished with the anatomical factor when we have described the costal element. As has been mentioned, other bony deformations are frequently found in association with abnormal ribs in this situation. Of these a cervico-dorsal scoliosis is perhaps the most common, and when present adds its quota to the distortion of the upper thoracic outlet. But more profound skeletal abnormalities have been frequently recorded, such as deformed upper thoracic and lower cervical vertebræ, wedged-shaped vertebræ, intercalated half laminæ, Sprengel's deformity (cf. Wilson, 1940), while in Case 4 here reported there is the Klippel-Feil syndrome with an associated gross congenital deformity of the lumbar spine and sacrum. The recorded association of syringomyelia with cervical rib affords yet another indication that we must regard the presence of abnormal costal elements at the upper thoracic outlet as the expression of some far more profound disorder of development that mere variations in the segmental derivation of the brachial plexus, which have been suggested by Wood Jones (1913) as adequately accounting for this

variations of this symptomatology, the occurrence of aneurysmal dilatation of the third part of the subclavian artery, the clinical features of this dilatation and the change in these when the dilatation becomes wholly or partly occluded by clot, and also the role of embolism in producing those gangrenous lesions of the digits often wrongly attributed to arterial spasm arising from pressure on sympathetic fibres in the first thoracic root. Case 3 illustrates the occurrence of embolism in the complete absence of any clinical indications of involvement of nerve roots. The emphasis in current accounts of rib pressure is strongly upon the somatic nervous symptoms, and the different vascular syndromes are very inadequately represented in neurological literature. It may therefore not be without value to draw attention again to this aspect of rib pressure.

III.—Factors in Symptom Production.

We may now attempt some generalization of the factors operative in the production of symptoms in the presence of an abnormal rib at the upper thoracic outlet. These factors fall naturally into three categories: anatomical, pathological and physiological, the second term referring particularly to the abnormal tissue reactions resulting from the operation of the anatomical factors.

(*a*) *Anatomical.*—The skeletal factor can be stated in general terms as consisting in an abnormality of the upper thoracic outlet, and whether it is a cervical or a rudimentary first rib that contributes to this is probably, from the clinical standpoint, a matter of indifference. It is unnecessary to recapitulate all that has been said of the radiographic differentiation of cervical from rudimentary first ribs, but there can be little doubt that the latter is still from time to time labelled a "cervical" rib, and the error will continue to occur until the radiography of ribs in this region has been systematized. A radiograph should reveal the entire course of an abnormal rib and of the two succeeding ribs with their sternal attachments, and it should establish the vertebral derivation of any costal element suspected to be abnormal. As the skiagrams illustrating this paper, and the reports upon them indicate, the serial identification of an abnormal rib is by no means the simple affair we have been prone to believe. Even the anatomist, studying in the dissecting room, or on the dried specimen, may err. Thus, Turner (1883) in his account of the so-called "bicipital" ribs first regarded these as resulting from the fusion of a cervical with a first rib, only later realizing that a fusion of first and second thoracic ribs was in question. The bicipital rib is produced by the fusion, anterior to their tubercles, of a rudimentary

mena in these cases, e.g. the aneurysmal dilatation of the third part of the subclavian artery.

The stresses to which the lower components of the brachial plexus are subjected have received greater attention than those affecting the subclavian artery, and have been described in detail many times in the case of cervical rib (Sargent, 1921). An abnormal and even a normal first rib may be deeply grooved by the first thoracic nerve root, and Dow (1925) in the case of rudimentary first rib describes the root as being "deeply embedded" in a groove on the rib surface. The raising and asymmetry of the thoracic outlet increase the possibilities of maladjustment between nerve roots and bone, while the associated muscular abnormalities already referred to also create abnormal conditions. The situation of the nerve roots in the case of "normal" first rib will be discussed in a subsequent chapter.

(*b*) *Pathological.*—The role that pathological factors, in the sense of abnormal tissue reactions, play in the production of somatic nervous, sympathetic and vascular symptoms has never received its due share of attention, and but for this our precise knowledge concerning them might now be far greater than it is, but there do not lack clear indications of the importance of pathological tissue reactions in cases of rib pressure. These reactions probably are less important in cases with such a sudden traumatic onset as Case 1 here recorded, than in the commoner cases in which the symptoms develop gradually as a result of long recurrent minor injuries due to friction and compression involving the soft tissues which are maladjusted to the thoracic outlet and clavicle. It is in respect of *the subclavian artery* that these factors produce the most diverse and striking results. The association of aneurysmal dilatation involving the third part of the subclavian and the adjoining part of the axillary artery in cases of cervical and of rudimentary first rib has been too frequently and too conclusively reported to be matter of doubt, though some authorities (cf. Wilson, 1940) still dispute it. Thus, it has been argued that the subclavian artery is normally of smaller calibre in its second part than in its first and third, and that a relative dilatation of the third part is therefore normal. Others have maintained that the artery is not in fact compressed or angulated by the rib and that vascular disorders in the upper limb are due to pressure on sympathetic fibres in the first thoracic root (Stopford and Telford, 1919, 1931). These fibres have, if the truth is to be told, been unduly stretched upon the procrustean bed of this hypothesis, if in no other way, but Cases 2 and 3 here recorded—and they are by no means unique—make it clear that true aneurysmal dilatation of the third part

presence. It is not the purpose of this paper to discuss anomalies of vertebral development and formation, but enough has been said to show that these anomalies themselves provide a wide field of study.

In any case, the sum of these bony abnormalities leads to marked asymmetry of the thoracic outlet. This tends to be narrower on one side than on the other, differs in outline on the two sides, is often higher on one side, and then the plane of the opening is abnormally tilted both in the transverse and anteroposterior directions. In the cases here reported all these deviations from the normal are exemplified. Necessarily associated with this state of affairs are abnormalities in the insertions of the scalene muscles. These muscles are the homologues of the intercostal muscles: scalenus anticus of the internal and scalenus medius of the external intercostal muscles. When there is a cervical rib, these muscles may have insertions into this as well as into the first thoracic rib. With a rudimentary first rib, scalenus anticus may have two or three heads of insertion into the posterior bony, the intermediate fibrous and the anterior bony parts of which this abnormal rib may be constituted. The subclavian artery may emerge from between two of these heads and so also may the lower trunk of the brachial plexus. Furthermore, the artery may lie higher than normal and it commonly runs an abnormal S-shaped course in the presence of an anomalous rib (Wingate Todd, 1911). It may be displaced or compressed by an exostosis or abnormal boss (Keen, 1907; Sargent, 1921; Lewis and Pickering, 1934, and Case 2 of our series). There is also evidence that in the presence of an abnormal rib, the subclavian artery, raised to an increased height as it crosses the rib, may tend to lie at the lowest level available to it, close against the posterior aspect of the scalenus tendon by which it may then be indented. Finally, the narrow space between rib and clavicle in which the third part of the artery runs may be altered in the presence of an abnormal rib. This space undergoes changes during respiratory excursion of the chest, and even more so during movements of the arm and shoulder girdle. On elevation of the arm the clavicle may compress the third part of the subclavian artery. The obliteration of the pulse at the wrist in these circumstances is common knowledge in cases of cervical rib, and Lewis and Pickering (1934) have provided direct information as to the compression of the artery in this way. *Indeed, the clavicle probably plays a far more significant role in the production of pressure symptoms, in the presence of abnormal ribs, than is commonly realized.* Effects usually attributed to rib pressure may be caused by it, a fact that explains some hitherto obscure pheno-

of the subclavian artery does in fact occur. There is, it may be admitted, a difficulty at first sight in accounting for an aneurysmal dilatation of the artery *distal to* the rib. Were the artery compressed and stenosed at the rib crossing, we should expect to find any dilatation that resulted therefrom to be proximal to the rib.[1] Surely, the true explanation is revealed in a description of the findings at operation upon a case of cervical rib, given by Lewis and Pickering (1934). This account also shows so clearly the part played by abnormal tissue reaction in cases of abnormal rib that it may be given in full. The authors say "the cervical rib was well developed, ending in a large boss which articulated with the first rib. The subclavian artery passed over this boss: behind the boss lay the cords of the brachial plexus, the lowest cord being in relation with the cervical rib but under no tension. The artery passed in the groove between scalenus anticus and rib: the posterior edge of the muscle indented the artery and pressed it backwards. After leaving the groove, in which the artery was of normal size, it dilated to form a fusiform aneurysm of about twice normal diameter, lying on the cervical and first rib . . . abduction of the arm to a right angle obliterated the pulse, the artery being seen to be obliterated between the clavicle and the boss of the cervical rib. . . . The expanded artery was covered with and bound to the underlying rib by very dense fibrous tissue, apparently the result of chronic inflammation, arising out of the trauma of compression between rib and clavicle."

Here we see the artery bound tightly to the rib, and as it lay fixed there, being compressed to the point of obliteration *by the clavicle*. How easily this recurrent trauma can occur may be shown in many cases of cervical rib merely by elevating the patient's arm and pressing it behind the vertical. It is not unreasonable to see in this repeated process, the basis of severe damage to the arterial wall, even of partial rupture of some of its components leading to aneurysmal dilatation of the third part of the artery. Thus, both the fact and the site of dilatation become explicable when we take into account the role of the clavicle, but not when we simply think of the phenomena in terms of the rib alone. Ehrlich

[1] The argument against the presence or, when present, the relevance of aneurysmal dilatation of the third part of the subclavian artery is surely a clear example of the logical fallacy of the "false cause." It is assumed that obstruction to the artery can be produced only by the rib itself, and that therefore any dilatation distal to the rib is either not related to the syndrome or is wholly illusory. The facts being thus sacrificed to the assumption, the way is left clear for a fresh assumption to the effect that all vascular disorders in the limb must be due to compression of sympathetic fibres in the first thoracic root.

(1895) and Halsted (1941) record the development of dilatation of this part of the artery after removal of a cervical rib, a further pointer to the part played by the clavicle.

Such an aneurysm having been produced, it may remain patent, or it may—also from recurrent trauma—become the seat of thrombus formation and thus become occluded. Therefore, the symptoms ensuing upon damage to the artery produced in this way will depend upon whether it remains patent or not. In the former case we have the conditions underlying increased pulsation of the artery, palpable thrill and bruit. When there is thrombosis and occlusion these symptoms disappear and are replaced by signs of severe ischæmia of the limb: coldness, cyanosis, pallor, weakness, muscular pain, sensory loss. A still further complication may ensue upon clot formation, namely, embolic phenomena, as recorded in Case 3, and fully described by Lewis in his book upon vascular disorders of the limbs (1936), an account with which the neurologist should be familiar. Anyone who has observed the development of patches of gangrene in the fingers in cases of cervical rib cannot escape the conclusion that embolism is the essential factor in their production. Lewis, speaking of cases of cervical rib with ischæmic symptoms says, "All the vascular symptoms displayed could not arise, however, directly out of compression or out of permanent obstruction of the subclavian artery; but they could arise out of thrombosis with embolism. The thrombi form where the wall is damaged by compression; these, so it is supposed, become detached by repeated movements and from time to time, causing embolism of smaller or larger branches in the arterial tree. A large embolus plugging the bifurcation of the brachial artery would give rise to severe pain and quickly reduce the hand and forearm to an algid, cyanosed state, from which recovery would be slow and imperfect. Many small emboli lodging in digital and palmar arteries would gradually block these vessels and produce in the fingers the picture of Raynaud's phenomenon, or spasmodic closure, in response to such stimuli as cold. Emboli of brachial artery, or of its branches, followed by thrombosis, would bring actual gangrene to given fingers. Embolism would explain why the radial is affected more often than the ulnar side of the hand. Repeated embolism, or embolism followed by thrombosis, would explain why the blocking of a distal artery can be followed, as it is known to be followed, by a central extension of the obstruction. Thus thrombosis with embolism account for all the phenomena and for the interesting variations of symptomatology that are known to occur."

Signs of inflammatory reaction in the arterial wall are shown in the second case here recorded. Wingate Todd (1912) has illustrated the condition of the arterial wall in an ischæmic case of cervical rib pressure, but in accordance with his hypothesis that pressure upon sympathetic fibres underlies all vascular symptoms in the arm, he goes on to suppose that these changes are due solely to disorder of sympathetic innervation of the artery: a conclusion that does not follow and that for reasons already given is not acceptable. It is possible, however, to invoke yet another factor in the production of the aneurysmal dilatation, albeit a speculative one, namely, that compression of this part of the artery may damage the vasa vasorum and thus lead to nutritive changes in the arterial wall, and then to dilatation.

We see, therefore, that clavicle and rib together constitute what we may call the vice in which the third part of the subclavian artery is recurrently gripped, and this conception of the mechanism of injury explains much that has hitherto been obscure: namely, the fact and the site of aneurysmal dilatation, the statement of some observers that the subclavian artery has not appeared stretched or angulated over an abnormal rib when seen at operation, and the occurrence of thrombosis and of embolism in some cases.

From the clinical point of view it is possible to distinguish three characteristic syndromes of vascular disorder. (i) The relatively common syndrome of recurrent coldness, cyanosis, pallor and tingling of the hand and digits, associated with the transient obliteration of an otherwise normal radial pulse by placing the arm in certain positions; (ii) the syndrome of patent aneurysmal dilatation of the third part of the subclavian artery. This may include the components already named, and in addition increased pulsation and bruit, with or without thrill, over the subclavian artery above the clavicle; (iii) the syndrome of a completely or partly occluded aneurysmal dilatation of the third part of the subclavian artery, consisting of signs of ischæmia in the limb and sometimes of embolism in the digits leading to small regions of gangrene.

The genesis of true *symptoms of sympathetic paralysis* may be accounted for by a lesion of the stellate ganglion. We have seen that this lies in close contact with the first part of the subclavian artery, and it seems probable that it may be subjected to traction when this artery is displaced, or involved in a fibrous tissue reaction round this vessel. *Signs of paralysis of the recurrent laryngeal nerve* with hoarseness have been mentioned by Keen (1907) and by Oppenheim (1911), and though both authors express some doubt as to how this may occur, it seems not un-

reasonable to suppose that this nerve may become involved in one or both of the ways already proposed in the case of the stellate ganglion. We need not seek to correlate such a paralysis directly with pressure on the nerve by a rib in order to account for its presence.

Turning now to the *somatic nervous symptoms* of rib pressure: namely, the muscular wasting and weakness and the sensory changes characteristic of most cases of rib pressure, we may ask whether, since stretching and angulation over a rib are seen to be an incomplete explanation of all that may happen to the subclavian artery, the same may not be true of the nervous symptoms. We have always assumed that it is the tension on the nerve roots as these cross an offending rib that leads to structural damage of their constituent nerve fibres and hence to such objective signs of damage as may occur. Yet there are features of the wasting and weakness characteristic of the presence of a cervical rib that have never been satisfactorily elucidated, though speculative ingenuity has not been wanting.

We owe it to the clinical acumen of Wilson (1913, 1940) that two motor syndromes have been differentiated: that of partial thenar atrophy involving exclusively, or almost exclusively, opponens and abductor pollicis, and that of the so-called ulnar type involving the hypothenar muscles, the interossei and the adductors of the thumb. These two types are beautifully illustrated in Wilson's paper and textbook already referred to, and every neurologist must be familiar with both of them. The first type is commonly associated with pain and paræsthesia—and sometimes objective sensory loss—over the ball of the thumb and the radial side of the hand and forearm, the second with pain and sensory loss along the ulnar or medial aspect of hand and forearm. Wilson found some difficulty in accounting for the partial thenar atrophy, and he summed up the matter as follows (1913), "The importance of this local atrophy will be recognized when it is remembered that the median nerve supplies the abductor pollicis, opponens pollicis and flexor brevis pollicis; yet of these muscles two are taken and the other left. This can only mean, I submit, that although their peripheral supply is from the same source their root supply is from two sources, probably the seventh and eighth cervical; for these are the roots that may be involved in this condition, and the lesions of cervical rib, therefore afford interesting evidence of the exact segmental supply of these muscles, and serve to establish their position in the cord. It may fairly be concluded that the root supply of the abductor pollicis and opponens pollicis is the seventh cervical, and of flexor brevis pollicis the eighth cervical." Elsewhere (1940) he states the position somewhat

differently, thus, "though the nerve-fibres concerned run distally in the median their presumptive radicular origin is from the seventh (or eighth), in which case they must occupy a fixed site among the constituent fasciculi in relation to the rib." Yet these conclusions do not necessarily follow once we appreciate that the motor symptoms associated with abnormal ribs at the upper thoracic outlet need not be always, or entirely, due to tension and stretching over a rib. If there be an aneurysmal dilatation of the subclavian artery, components of the brachial plexus may be compressed by it, may be involved in a fibrous tissue reaction with the artery, and may be pressed back against the rib by movements of the clavicle: *that is, the nervous elements may be subjected to trauma at a point distal in their course to the one we have always supposed to be the point of injury.*

The ulnar type of wasting of small hand and of forearm muscles may be considered from this point of view. Associated with it we occasionally find weakness of serratus magnus with winging of the scapula. Reference to the relations and form of the brachial plexus show that at the point where the inner cord of the plexus arises from the lower trunk, at the outer border of the first rib, the long thoracic nerve on its downward course lies immediately behind the cord. Here, then, are gathered together the nerve fibres which pass to the ulnar nerve and the inner head of the median nerve, and also the long thoracic nerve. Pressure backwards upon them at this point, by a dilated subclavian artery or clavicle, could thus produce this type of ulnar weakness and wasting of muscles, together with paresis of serratus magnus. Indeed, it is difficult to account for the weakness of the last-named muscle in any other way, since its segmental innervation is from three nerve roots, fifth, sixth and seventh cervical. It is noteworthy that in Case 2, excision of the aneurysm led to the steady recovery of the paralysed muscles, although the abnormal costal element had not been removed.

The falling backwards of the shoulder when the patient is supine in bed, would aggravate the pressure on the nerves produced in this way, and thus account for the common complaint that the pain of a cervical rib is at its worst at night when the patient is in bed.

In respect of the other type of muscular wasting, the partial thenar atrophy first pointed out by Wilson, it is possible that comparable factors are in question. It is reasonable to think that this selective wasting might occur by compression of a nerve at some point where the motor fibres to these muscles run remote from those innervating the other intrinsic muscles of the hand. Such a situation would be the outer head of the

median nerve. This is generally described by anatomists as taking origin in the axilla and crossing the axillary artery from within outwards at a more distal point than we can suppose it to be subjected to pressure by a subclavian aneurysm or the clavicle. Yet its origin is notoriously variable. It is perhaps more likely that the outer cord of the plexus which lies lateral to the third part of the subclavian artery could be subjected to compression by the two agencies named, and it is within this cord that the motor fibres to the outer head of the median run: that is, the fibres which supply opponens pollicis and abductor pollicis, but not the intrinsic hand muscles. This can be but surmise, but the suggestion emphasizes that we may not assume the point of pressure on somatic nerve fibres to be necessarily or invariably where these lie upon a cervical or a first rib. As in the case of the artery, this point may be distal to the outer border of the rib.

(*c*) *Physiological.*—In addition to the two factors already considered, is a third, which may not unappropriately be called a physiological factor, must be mentioned. Great stress is laid by all writers upon the part played in the production of symptoms in abnormal and normal rib pressure syndromes by a sagging shoulder girdle. The frequency with which symptoms make their first appearance in the patient after some severe illness, childbirth, or some general debilitating state is familiar, and the normal descent of this girdle during middle age, particularly in women, is known. This sagging or drooping of the shoulder acts in two ways. It exerts tension on nerve roots and artery, and stretches these still more tightly over the upper edge of the thoracic outlet. It also makes the clavicle fit more closely against the thorax and narrows the space between them through which nerves and artery pass. In this way it may add a further element to the maladjustment provided by an abnormal thoracic outlet, and even when this outlet is normal it may produce pressure symptoms—the so-called first rib and scalenus anticus syndromes. It is probable that for the two latter syndromes this factor of the drooping shoulder is primarily responsible—as a factor precipitating the onset of symptoms.

IV.—Cervical and Rudimentary First Rib Syndromes: Can They Be Differentiated?

Once we have clearly envisaged the possibility that rudimentary first ribs are less rare than we have supposed and that they produce pressure symptoms, it becomes of interest to consider whether it is clinically possible to establish any criteria by which their effects can be distinguished

derivation of the brachial plexus in determining the degree of development of the eighth cervical and first thoracic costal elements, though some (Wingate Todd, 1911; Dow, 1925) believe other factors to be involved also. It is agreed that the groove on the first rib in which the first thoracic nerve root lies may be deep, its depth varying with the size of the contribution which this root and the second thoracic make to the brachial plexus. Further, Wood Jones (loc. cit.) states, "In cases which hardly come within the limits of the abnormal this interaction of the strained caudal end of the plexus and the first rib may proceed to such a degree that the rib becomes bent downwards at the site of crossing the lower cord." His illustration of this bending is here given (fig. 11).

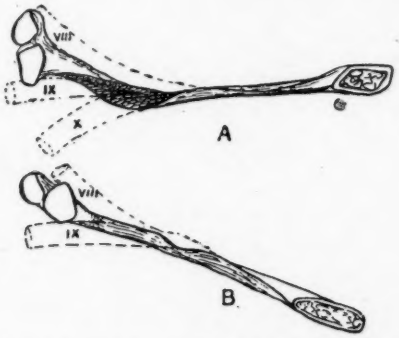

FIG. 11.—From Wood Jones (loc. cit.), 1913. A, First thoracic rib, seen from within to show the bending of the axis of the rib at the site of the *sulcus nervi brachialis*, contrasted with the corresponding margin of the typical form, B.

The bent form of the first rib is the one to which Stopford and Telford (1919) refer as the "rocker" form. It is reasonable to suggest that according to the degree of post-fixation of the plexus, we may expect to find a series of form variations from the straight but grooved first rib, through the rocker form to the rare frankly rudimentary rib which either ends prematurely by union with an exostosis on the second rib, or fuses with this to form the bicipital rib already referred to. In these circumstances, we should anticipate that the pressure syndrome arising from "normal" first ribs would bear a general resemblance to those associated with a rudimentary first rib, and this, with some qualifications, is the case. A systematic radiographic study of the range of form variation in what we call "normal" first ribs would be of interest, but it has yet to be carried out.

Bramwell (1903) appears to have been the first to draw attention to the

from those of the commoner cervical rib. The point, perhaps, is not an important one, since adequate radiography will generally suffice to make the distinction for us. As long as we continued to think of an abnormal rib as the sole operative factor, it seemed reasonable to suppose that the incidence of the pressure effects upon nerves and artery might not be the same in the two conditions. Yet once we realize the multiplicity of factors involved, particularly the pathological tissue reactions that we have considered, it seems likely that no constant or clearcut differences between a cervical and a first rib syndrome will be found.

For example, the stellate ganglion stands in close relationship to the head and neck of the first rib, and when the latter is abnormal in form and direction it might conceivably compress or pull upon the ganglion, whereas, the ganglion stands in no such topographical relation with a cervical rib and might be expected to escape damage in the presence of this bony anomaly. However, it is probably the contiguity of ganglion and subclavian artery which is the significant relationship, with the involvement of the two in a fibrous tissue reaction. The recording of Horner's syndrome in cases of so-called normal first rib and scalenus anticus syndromes, that is, with a normal thoracic outlet, suggests that it is the arterial relationship that is the relevant one.

In the matter of somatic nervous symptoms, we should expect wasting and weakness referable to the seventh and eighth cervical roots in the case of cervical rib, and referable to the first thoracic nerve root in the case of a rudimentary first rib. Yet both types may be present in association with a cervical rib, and, as has been suggested here, pressure on distal elements of the plexus may be in question.

A rudimentary first rib is usually longer than the average cervical rib and perhaps raises the thoracic outlet more than does the former, and thus vascular disorders referable to the subclavian artery might be expected to be more severe and prominent with a rudimentary first rib. Yet as Case 3 here recorded shows, no firm conclusion can be drawn, and in short, there is at present no clear evidence to suggest that we could hope to differentiate the syndrome of a cervical from that of a rudimentary first rib on clinical grounds alone. Clearly, the point is one that calls for further study in the future.

V.—The Syndrome of a "Normal" First Rib and the So-called "Scalenus Anticus Syndrome."

The term "normal" as applied to the first rib embraces considerable variation in form. Wood Jones (1913) has stressed the importance of the

clavian artery. As we have seen, Stopford and Telford (1919, 1931), attribute these to pressure on sympathetic nerve fibres in the first thoracic root, an hypothesis which we have found unacceptable. The arguments against it may now be reviewed more fully. The symptoms are intermittent, fluctuating widely from hour to hour, almost from minute to minute, and when they are absent they may leave no residual trace of their former presence. The factors that produce them are precisely those that could lead to compression of the subclavian artery by rib and clavicle: namely, traction on the arm and the use of the limb in heavy work. This remarkable variability recurring, it may be, for years is not compatible with the notion of structural damage to nerve fibres, such as must occur from long-standing and recurrent pressure—and such in fact as does occur in the case of somatic nerve fibres when subject to these abnormal conditions. In their original paper, Stopford and Telford (1919) do not say whether they regard coldness, cyanosis, pallor, dryness and tingling as paralytic or irritative symptoms, but it is clear that taken together as a group they cannot be described as either. Coldness and cyanosis could only be described as irritative symptoms, but dryness is a paralytic manifestation. Faced by these inconsistencies, Stopford and Telford (1931) later proposed that an irritation of sympathetic fibres is in question, causing arterial spasm with obliteration of the vasa vasorum and consequent nutritional changes in the subclavian artery wall with thrombosis and occlusion. Lewis and Pickering (1934) have pointed out in a conclusive criticism that while there are no cogent grounds for this hypothesis, there are many against its validity. It assumes that all the vasomotor fibres to the upper limb pass through the first thoracic nerve root, but the facts are that these fibres come from the thoracic sympathetic chain to the stellate ganglion, passing thence by grey rami to the eighth cervical and first thoracic roots. It assumes that long-standing irritation of nerve fibres does not lead to their structural impairment and the development of paralytic symptoms, an assumption contrary to what we know of the reaction of nerve fibres to mechanical irritation of long standing. It does not account for the frequency with which these vascular disorders are unaccompanied by any indications of pressure upon the somatic nerve fibres in the first thoracic root, and it is difficult to see how recurrent pressure upon a nerve root, repeated over long periods can disturb sympathetic fibres and leave somatic fibres intact. Stopford and Telford (1931) meet this objection by a further assumption, already advanced by Sargent (1921), that the sympathetic fibres in the first thoracic root lie ventrally and super-

possibility that a normal first rib might exert pressure upon the first thoracic nerve root and thus lead to a uniradicular palsy. He referred to the notably sharp mesial border of this rib as calculated to damage a nerve root stretched unduly tightly across it. Murphy (1910) in an oft-quoted paper first reported the division of a normal first rib for the relief of root symptoms, and since that time others have repeated his procedure (Stiles, 1929; Stopford and Telford, 1919). The latter authors describe seven cases so treated, but they do not provide all the clinical details we should like. Five of their patients were women—the predominance of this sex being notable in all cases of rib pressure—and the syndrome contained three components: (i) Pain of ulnar distribution sometimes accompanied by an area of analgesia; (ii) weakness and wasting of small hand muscles leading to "main en griffe" or claw hand in some instances; (iii) coldness, cyanosis, and dryness of the fingers. In one instance they found diminution of the radial pulse. At operation they found no signs of compression of the subclavian artery, and they attributed the vascular symptoms in the hand to compression of sympathetic fibres in the first thoracic root. This appears to be the typical first rib pressure syndrome, and all who have described it stress the drooping of the shoulder girdle that accompanies it. Undoubtedly, this drooping of the girdle and upper limb is the factor precipitating pressure effects by increasing the tension upon nerve roots and artery and also probably by narrowing the space between clavicle and first rib. The factor of an abnormal thoracic outlet is not present here, save in so far as this is provided by the bending of the first rib in some cases.

It is interesting to consider the possibility that a syndrome now very commonly found in middle-aged and elderly women who have had to take to heavy manual work of an unwonted kind, under the conditions of war time, may be a minor expression of first rib pressure. The syndrome consists in burning pain, tingling and sometimes pallor or blueness of the fingers, worse during the night and sometimes rendering the hand "useless" when they first get up in the morning. In all such cases rest seems to give complete relief, but no mode of local therapy unaccompanied by rest is in the least effective. Here also sagging of the shoulder girdles from fatigue, debility and unaccustomed manual work may be the operative factors.

It is noteworthy that the graver symptoms associated with cervical and rudimentary ribs, nervous and vascular, seem not commonly to occur in cases with a normal rib, but the coldness and cyanosis of the hand point to some interference with the blood flow through the sub-

ficially in the root and are thus especially vulnerable to pressure, but this hypothesis fails to account for those cases of first thoracic root pressure where the symptoms are entirely somatic and no vascular disorders are present. It should be added that at operation Stopford and Telford (1919) found no evidence of direct interference with the subclavian artery by the rib, but their conclusion does not follow from this observation, since it takes no account of the action of the clavicle, and tells us only of the relation of artery and rib in the position of the arm necessitated by the needs of surgical intervention.

In short, it seems clear that there are no grounds upon which we can reconcile coldness, cyanosis, pallor and tingling of the hands with involvement of sympathetic fibres, and that there are many grounds upon which we must relate them to compression of the subclavian artery.

The same is true of the patches of digital gangrene sometimes seen in rib pressure cases of vascular type, where there is thrombosis within the subclavian artery.

We come now to consider the so-called scalenus anticus syndrome, which appears to have replaced the conception of normal first rib pressure in the literature, especially in America.

Adson and Coffey (1927) found that section of scalenus anticus relieved symptoms in certain cases of first rib pressure where no abnormal costal element was present. Their subjects were mostly women, and the symptoms were precipitated by fatigue and general muscular atonia. The syndrome they describe is that already discussed as associated with a normal first rib, and they found Horner's syndrome in some of their cases. Since this time, the tendency has been to emphasize the role of scalenus anticus in leading to pressure symptoms similar to those associated with cervical rib.

Thus, Puusepp (1931) suggested that the lower components of the brachial plexus may be nipped in the angle between the posterior border of scalenus anticus and the first rib (trigonum costo-scalenicum). He also cites as contributory factors a sagging shoulder girdle from general muscular atonia, the advancement of the arm in the course of its normal usage and over-elevation of the first rib by scalenus anticus. This overaction of scalenus he ascribes to hypertrophy, inflammation or injury, and, subsequently, the notion of hypertrophy and hypertonus of scalenus anticus has become an integral component of the syndrome of the scalenus, so-called. The syndrome, as described by Puusepp is precisely that already described in this chapter, with the addition in two of his cases of a frank Horner's syndrome. How the last is produced he does

not tell us, but his hypothesis provides no explanation of it. It is noteworthy, however, that the syndrome he describes is that found to be associated with rudimentary and normal first rib pressure.

His hypothesis seems to take too little account of the topographical relationships between nerve root, rib and muscles. The first thoracic root (or the lower trunk of the plexus) crosses the rib diagonally and not at right angles to the rib axis, lying in a deep groove as it does so. It is separated from the insertion of scalenus anticus by the subclavian artery. Scalenus anticus, which is the homologue of the internal intercostal muscle, is inserted into the scalene tubercle of the first rib at the mesial border of the latter, while scalenus medius—the homologue of the external intercostal muscle—is inserted nearer to the neck of the rib and near its lateral border. Therefore, the nerve root passes forward diagonally through

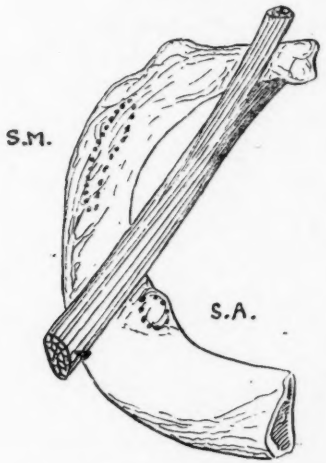

FIG. 12.—From Wood Jones (loc. cit.), 1913. The normal first rib and its relation to the lower trunk of the brachial plexus.

a channel on the rib surface, walled on either side by a scalenus muscle. It is not easy to see how in these circumstances the nerve root can be nipped in the fashion suggested. Further, overaction of scalenus anticus by lifting the rib, would widen the trigonum costo-scalenicum and thus tend to relieve the suggested nipping. These relationships are indicated in fig. 12, taken from Wood Jones' paper, to which the insertion of the muscles has been added by dotted lines.

A full formulation of the scalenus anticus syndrome is given by Ochsner, Gage and DeBakey (1935). The symptoms are precisely those we have already considered, and the authors say that at operation they found scalenus anticus hypertrophied and hypertonic ("spastic and stiffened"). They also invoke general muscular atonia in a female

subject as providing the background of their cases, and they attribute scalenus spasm to irritation of the brachial plexus by a normal first rib—this being induced by sagging shoulders, high fixation of the sternum and post-fixation of the brachial plexus.

First rib pressure, it is to be noted, remains the primary and sole essential element in this sequence of processes, scalenus spasm being merely a secondary factor. It is not clear whether by irritation of the plexus it is intended to convey that the scalenus is directly stimulated by irritation of its motor fibres in the plexus, or whether a reflex irritation is in question. Neither process could thus operate, since scalenus is supplied by the fourth, fifth, sixth and seventh cervical roots, while the roots supposed to be irritated are the eighth cervical and first thoracic which do not supply this muscle. In any case such stimulation of muscles by an irritated plexus could not possibly be restricted to scalenus anticus. From another point of view, the notion of a generally atonic subject in whom one single muscle is mysteriously hypertrophied and hypertonic is not one that easily commands credence.

These authors briefly describe six cases, all women, and the symptoms consist of pain of ulnar distribution, supraclavicular tenderness, coldness and tingling of the hand, with diminished radial pulse and reduced arterial oscillations as determined by Pachon's apparatus.

Naffziger and Grant (1938) give a résumé of the literature up to the date of their paper and summarize their findings in 18 cases of "neuritis of the brachial plexus mechanical in origin." Of these 6 cases had cervical ribs, but the remaining 12 showed no bony anomaly. They find that in both categories marked circulatory disturbances are uncommon, but in one case without abnormal rib the subclavian artery was occluded and the distal extremity of the upper limb was gangrenous, and in two cases an arterial bruit was heard upon auscultation above the clavicle. Differences in blood-pressure—up to 10 or 15 mm.—were not uncommon. Evidence of "sympathetic disturbance," was found in 9 cases, consisting in flushing of skin of hand or arm, brittle nails, rarefaction of bones, cyanosis, enophthalmos. Inequality of the pupils and of the palpebral fissure are also recorded, and they regard migraine as a sympathetic component of the syndrome. On the somatic side, subjective sensory phenomena—and more rarely objective changes of slight degree—were found, sometimes ulnar, sometimes radial in distribution, and moderate wasting of small hand muscles.

Like other writers on the scalenus syndrome they enumerate the operative factors as a post-fixed brachial plexus and an abnormal posture

of the shoulder girdle which together lead to tension and angulation of the lower components of the plexus over the first rib. To these factors they add spasm in scalenus anticus, which they describe as tense and hypertrophied and as an additional cause of angulation of plexus and artery.

The most recent exposition of the scalenus anticus syndrome is provided by Swank and Simeone (1944), but their series of 15 cases form so heterogeneous a medley of conditions, clinically, pathologically and ætiologically, that they cannot be comprehended within a single series, and if the term "scalenus anticus syndrome" is to be extended to cover them it loses all meaning.

That scalenus anticus may act as one factor in compressing the subclavian artery even in the presence of an abnormal rib, we have already seen, but it is also apparent that many factors combine to lead to pressure symptoms, nervous and vascular, and while in the individual case one or other of these may predominate, we cannot provide a satisfactory elucidation of the symptoms present in terms of one of them alone. On the skeletal side, rib and clavicle play important parts, while on the pathological side the effects of damage caused by these lead to secondary tissue changes that themselves produce clinically important symptoms.

The same considerations apply to the "scalenus anticus syndrome." Here also, rib and clavicle, post-fixation of the plexus and sagging of the shoulder girdle are by all admitted to be operative factors, and doubtless, from time to time pressure of scalenus anticus on artery and nerve roots becomes also a contributory factor. From all these factors, we cannot pick out one—perhaps the least constant of them all—to give a name to a syndrome. To do so is to encourage an artificial and restricted conception of what is happening. This view is not invalidated by the fact that division of scalenus anticus may in some cases afford relief of symptoms. It would be just as appropriate to speak of the "syndrome of sagging shoulders," and, indeed, such a title would involve far less abstraction from the total reality of the state of affairs present in these cases than that of the "scalenus anticus syndrome."

In conclusion it may be noted that the presence of Horner's syndrome calls for the operation of other factors than the action of scalenus anticus.

VI.—Summary.

A small series of cases of cervical and rudimentary first rib pressure is described, and the factors underlying the production of symptoms in

these cases, as well as in those in which no abnormal costal element is present, are discussed.

The factors are seen to be multiple—anatomical, pathological and physiological. When an abnormal rib is present, it is rarely the only relevant skeletal abnormality, for scoliosis and vertebral deformities are commonly associated with it. The bony abnormality is therefore best expressed, not in terms of the abnormal rib alone, but in terms of an abnormal upper thoracic outlet. This outlet is commonly asymmetrical and abnormally raised and tilted. The nervous and vascular symptoms associated with this state of affairs are not, however, to be accounted for in terms of it alone, for there is evidence that the clavicle plays an important part in the compression of nerve roots and artery. The clavicle and the abnormal rib form the two arms of a vice in which these structures are recurrently compressed. This view does not exclude the role of a rib in exerting traction upon, stretching and angulating of, the structures which cross it. Secondary and pathological factors, arising from the maladjustment of bones and soft tissues, contribute an important part of the symptomatology. Damage to the subclavian artery may lead to its aneurysmal dilatation, with or without the formation of clot within it.

Thrombosis, when it occurs leads to severe ischæmia in the upper limb and sometimes to the production of emboli which lodge in the digital arteries and give rise to those gangrenous patches, sometimes erroneously attributed to disorders of sympathetic innervation. In fact, the various syndromes arising in association with cervical and rudimentary first ribs can only be accounted for when all these factors are taken into account, and this applies to nervous as well as to vascular symptoms.

Reasons are given for concluding that vascular symptoms in the upper limb are not due to disorders of sympathetic innervation, but to mechanical interference with the blood flow through the subclavian artery. When true symptoms of sympathetic paralysis occur, they are referable to the stellate ganglion. Of the components of the syndrome of a paralysing lesion of this ganglion, Horner's oculo-pupillary syndrome is the most familiar. In one case here recorded other components were also present, and it is probable that systematic study of sympathetic functions in cases of rib pressure would reveal their presence more often. The stellate ganglion is probably involved in the inflammatory fibrous tissue reaction which occurs round the subclavian artery, but other ways in which its functions might conceivably be affected are discussed.

The factors leading to pressure symptoms affecting nerves and artery when no abnormal costal element is present: the so-called "normal first

rib" and "scalenus anticus" syndromes, are discussed. Perhaps the essential factor is a dropping of the shoulder girdle. This leads to increased tension on nerve roots and subclavian artery and, by narrowing the space between first rib and clavicle, probably leads to the compression of these structures by the clavicle during movements of the arm. The action of scalenus anticus as an operative factor is problematical, and not of primary importance, and the title "scalenus anticus syndrome" is seen to embody an hypothesis that is not adequate to account for the facts of observation.

Finally, the need for a more systematic radiographic study of the components of the upper thoracic outlet is stressed as of great importance in all suspected cases of rib pressure.

We wish to express our thanks to Drs. Cochrane Shanks and Hugh Davies for their reports on the skiagrams, to Dr. Purdon Martin for permission to record Case 2, and to Dr. Carmichael for Case 5.

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THE ELECTRICAL ACTIVITY OF VOLUNTARY MUSCLE IN MAN UNDER NORMAL AND PATHOLOGICAL CONDITIONS.

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I.—Introduction.

The ease with which it is possible to distinguish the action potentials in normal and denervated muscle in the human subject makes electromyography with concentric (co-axial) needle electrodes (Adrian and Bronk, 1929) of particular value in demonstrating lesions of the lower motor neurons (Weddell *et al.*, 1943). With this in view, and taking as a basis the results obtained in the course of our experimental work, an electromyographic unit suitable for clinical work has been constructed, and cases exhibiting a wide range of abnormal neurological conditions examined. In addition to the assessment of clinical cases from the point of view of damage to the lower motor neuron, the electrical activity of single motor units in normal muscles has been observed and related to their anatomical arrangement. The motor unit activity in a number of muscles has also been recorded in relation to "muscle tone." Lastly some of the more important factors influencing the fibrillation of denervation in man have been investigated and the electrical activity of muscle during nerve regeneration recorded.

II.—Methods.

(1) *Apparatus.*—For routine clinical investigation an electromyographic unit has been designed which is easy to operate, reliable, and free from all extraneous interference. High input impedance and a rigidly linear frequency response are not essential. A pre-amplifier unit consisting of two stages of amplification is coupled to a voltage amplifier which in turn is fed to the "Y" plates of a cathode ray oscilloscope. The output of the voltage amplifier is also fed to the grid of a power valve driving a 10 in. loud speaker. The amplifier gain is usually adjusted to give a vertical screen deflection of approximately 30 microvolts/cm., but can be increased far beyond this. The "noise level" is not greater than 1·5 microvolts and the gain is linear between 20—2,000 cycles with a slight falling off up to 4,000 cycles. The horizontal sweep speed is maintained at between 5 and 10 per second. For photographic recording of action potentials the output of the voltage amplifier is also coupled directly to the "Y" plates of a second (preferably Cossor No. 339A) oscilloscope which is used without time base and fitted with a Cossor Model No. 427 Camera. The paper transport mechanism of the camera is driven through a clutch and variable speed system of pulleys by a Klaxon type H K 5 C B 1 motor.

Because of the disturbances which arise in H.T. batteries after a short period of use and in order to eliminate "run-down" batteries as a source of trouble, an all-mains H.T. supply is used. A condenser-choke smoothing circuit provides power for the loud speaker and from this is led off a 4-stage resistance coupled (R = 5,000 ohms C = 4 microfarads) smoothing circuit for the supply of the first two stages. By this means all perceptible traces of mains hum are eliminated from the H.T. supply. The filaments of the first two stages are heated by smoothed rectified (metal rectifier) alternating current.

It is necessary to eliminate disturbances due to low frequency modulation (one to five cycle) of the mains voltage. This is done by using resistance-capacity coupling networks which attenuate the lower frequencies very strongly and are

thus also effective in preventing "motor-boating." The usual precautions against self-oscillation are taken, and the amplifier proves entirely stable. Microphonics are eliminated by suspending the valves in the first two stages in rubber mountings.

The extraneous disturbances which must be eliminated are 50 cycle interference from A.C. mains, and (in our laboratory) 600 and 1,800 cycle ripple from nearby D.C. mains. The first two stages already screened by non-magnetic metal cases are together encased in a further non-magnetic shield, and the leads to the needle in a flexible steel gas pipe. The needle enclosing the insulated core is earthed. This arrangement obviates the necessity of further earthing the patient and gives rise to no appreciable distortion. The apparatus thus constructed has worked in many different buildings and in different cities with different power supplies. Interference appeared on the screen only once in the neighbourhood of an unscreened electrosurgical spark diathermy unit which was being operated close by.

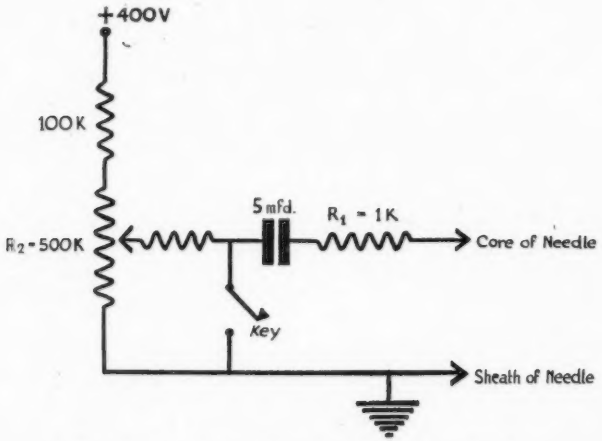

FIG. 1.—Illustrates the principle of the stimulator.

The interference in this case was eliminated by additional earthing through large damp saline pads bandaged to the extremities.

A switch is provided to disconnect the needle from the amplifier and connect it to a source of graduated electric shocks. The stimulating mechanism is shown in text-fig. 1; on closing the key K a prolonged condenser discharge passes between the electrodes. This is followed by very slow return current, which recharges the condenser when the key is released. There is thus no possibility of an excessive current flowing or of polarization. The resistance R, prevents the appearance of a spark. The magnitude of the discharge can be varied by means of R 2. Stimulation takes place at the point of the needle, the position of which is determined by observing which muscle contracts. In practice this stimulator has proved entirely satisfactory except in the case of muscles which have been the seat of considerable fibrotic change following denervation of long standing. In such cases it may be necessary to move the point of the needle a number of times before a satisfactory contraction can be observed.

The needle electrodes used for clinical investigation are from ½ to 3 in. in length and diameters corresponding to I.S.W.G. 20 to 26. Hypodermic needles, mounted in cylindrical metal bases designed to fit in standard 3-pin radio plugs, were specially manufactured for us. This facilitates rapid assembly and replacement.

(2) *Procedure.*—In the investigation of clinical cases it is important that the subject be placed so that the muscles to be examined can be completely relaxed. When examining the upper limb, for instance, it is best to have the subject sitting in an easy chair with the arms placed on a waist-high table in front of the examiner. The trunk musculature and lower limbs are best put at rest with the patient lying on a comfortable couch. To cause as little discomfort as possible, and in order to avoid reflex motor activity, novocain (1 per cent.) is injected intradermally over the muscles to be examined. The presence of the needle electrode in the muscle causes no discomfort, and only the mildest discomfort is experienced during its insertion and during a powerful contraction. To ascertain from which muscle the tip of the needle is recording, a stimulus is passed between the core and the shaft of the electrode and the contraction noted. In practice the electromyographic recordings are taken first and the position of the needle point ascertained subsequently. This avoids the possibility of local damage by the stimulus which in turn might cause a reflex discharge of motor activity. It was found that ten to twelve separate needlings can be done without causing any marked discomfort in the average Service patient. It should be made clear that for diagnostic purposes only the sounds emitted from the loud speaker are noted, for the detection of small differences in duration and frequency are more easily assessed by auditory than visual methods. For practical purposes the laborious method of measurement from tracings may be dispensed with. These facts have already been emphasized by Adrian and Bronk (1929). The oscilloscope tracings are used for permanent records, obtaining a measurement of the power of weak muscles (*vide infra*) and for demonstration purposes. We have found that in many cases patients are most interested in the tracings of the action potentials on the screen, and during regeneration of peripheral nerves the appearance of an increasing number of action potentials at successive intervals is often effective in encouraging the patient to perform active and/or passive movements of the affected muscles in the intervals between his attendances at the physiotherapy department. In addition, in nervous individuals, it is easier to obtain relaxation by requesting the patient so to position the body that the sweep on the oscilloscope is undisturbed. For practical purposes, however, only the needles, high grade amplifier and loud speaker unit are necessary for electromyography.

III.—The Action Potentials from Normal Muscles.

(1) *Limb Muscles.*

Motor unit action potentials.—Electromyographic recordings have been made from the limb muscles in over 100 normal subjects. The insertion of a needle electrode evokes an outburst of action potentials which we have termed "insertion" motor unit action potentials. They can only be distinguished from normal motor unit action potentials of neural origin by the mechanical manner of their production (Plate VII, fig. 1). If the needle electrode is held immobile or moved slowly and smoothly through a

relaxed muscle, no electrical activity is recorded even at the highest amplifications (2×10^6) once the "insertion" outburst has died away (Plate VII, fig. 2). Other workers have also reported the absence of electrical activity within a relaxed muscle (Adrian and Bronk, 1929; Smith, 1934; Lindsley, 1935; Ingebrigtsen, 1938; Gilson and Mills, 1941; and Hoefer, 1941). Jacobson (1943), however, states that action potentials of short duration and low amplitude can be obtained from relaxed voluntary muscle and represent resting "tone." Jacobson's results have been criticized by Hoefer (1943) on technical grounds.

On slight voluntary contraction 1-2 repetitive action potentials at the rate of 5-10 per second appear. As the tension increases the frequency of the action potentials may increase up to 50/second although we have only seen two cases in which such a speed was definitely recorded (Plate VII, fig. 3). The average maximum rate is around 20/second. These findings agree with those of Lindsley (1935) and Hoefer and Putnam (1939). With a greater increase of tension more action potentials appear until with a powerful contraction the sweep on the oscilloscope screen is disturbed throughout its length by irregular spikes up to 1-2 millivolts in amplitude and 5-20 milliseconds duration (Plate VII, fig. 4). In common with Smith (1934) and Lindsley (1935) we have not observed the phenomenon of "rotation" of activity or substitution of motor unit action potentials during a sustained voluntary contraction of short duration. While the maximum amplitude and duration of an individual motor unit is constant, the maximum amplitude and duration of different motor units in the same muscle varies despite careful positioning of the needle point. The range of maximum amplitude is between 100 microvolts and 1 millivolt and the duration 5 to 10 milliseconds in the average limb muscle. It is possible to assess approximately the degree of motor unit activity in a muscle by observing the amount of disturbance of the time-base tracing in a series of needlings. For example, it was found that, with the electrode in the middle of the belly of an extensor carpi radialis longus muscle and the wrist hanging loosely over the end of an arm rest, about one-quarter of the time-base tracing is disturbed when the wrist is raised sufficiently for a movement to be visible. With the wrist maintained level against gravity the base-line is disturbed for about three-quarters of its length; these findings were confirmed in a number of cases. Such assessments, however, are only of practical use in the case of weak muscles such as those partially denervated, or in which some of the nerve impulses to the muscle are blocked. In this type of case they provide a record against which to measure improvement or regression of power. In all normal limb muscles

contracting against resistance the base line is disturbed throughout its length.

The amplitude of a single motor unit action potential varies with its relationship to the tip of the needle electrode. It decreases as the electrode distance increases, and its wave form becomes less angular. Its general configuration however remains constant. In a normal contracting limb muscle the most frequent form of action potential is mono- or diphasic (Plate VII, figs. 5 and 6). A few triphasic action potentials have been observed (Plate VII, fig. 7) and on some occasions polyphasic action potentials (Plate VII, fig. 3). In normal muscle the latter are sometimes among the largest action potentials seen. At times apparently polyphasic action potentials prove to be pairs of di- or triphasic action potentials firing almost synchronously.

Continuous synchronous motor unit firing has never been seen in normal cases; observation for a few seconds always shows a phasic change. Further, the sounds are characteristic of simple motor units passing into and out of phase and cannot be confused with true polyphasic action potentials which have a characteristic rough sound.

The presence of occasional polyphasic motor unit action potentials was noted by Denslow and Hassett (1943) who recorded from human deltoid, triceps, brachialis, extensor digitorum communis and spinal extensor muscles. These authors suggest that the occurrence of such polyphasic action potentials may be explained on the assumption that a motor unit is sometimes made up of small groups of muscle fibres which are scattered throughout the muscle, but they make no suggestion as to how such a distribution might produce them. We believe that such an arrangement would tend rather to diminish any polyphasicity caused by differences in the time at which the active edges of different fibres pass the needle. The preponderance of diphasic action potentials may be partly accounted for by the fact that, where effort is slight and individual units clearest, the probability of a unit which is very close (and thus most likely to show a polyphasic action potential) being in action is small. The work of Bishop and Gilson (1929) is in favour of our interpretation.

Properties of the electrode.—A series of experiments has shown that the type of electrode we employ has marked directional properties combined with a limited recording range. In five normal subjects the electrode was inserted through the skin over the deltoid muscle, and the bevelled surface of the needle adjusted to lie on the surface of the muscle. This position can easily be judged by the contact of the needle with the epimysium. The subject then abducted his arm against resistance and

the needle was adjusted until a motor unit action potential at its maximum amplitude was being recorded. The needle was then slowly rotated through 180° when the amplitude of the action potential fell almost to zero; further rotation through 180° restored the amplitude to its original level. The actual epimysium clearly has little barrier effect on the amplitude of the recorded action potential, for the needle was passed from a few miillimetres external to it to a few millimetres internal without alteration of the spike. Care was taken to keep the bevel of the needle facing the muscle surface during the experiment. On withdrawing the needle less than ½ cm. into the subcutaneous fat however the action potential immediately fell to zero.

In another experiment the needle electrode was inserted into the brachio-radialis muscle while it was contracting weakly, and moved until a single diphasic motor unit action potential of high amplitude was recorded. A slight movement of the needle point at once caused a change in the amplitude of the action potential but did not vary its general configuration. The electrode was then moved around until the maximum amplitude of the action potential was recorded, and from this position slowly pushed more deeply into the muscle at right angles to the muscle fibres. The action potential spike diminished practically to time-base level when the needle had covered a distance of between ¼ and ½ cm. and, on slowly withdrawing it in a similar manner, the action potential gradually regained its original height. As the needle was still further withdrawn the spike again decreased in amplitude until at a distance of ¼ to ½ cm. from the point at which a maximum amplitude had been recorded it was practically at time-base level. This experiment was repeated a number of times while recording diphasic action potentials from different large muscles with longitudinally arranged muscle fibres such as the extensors and flexors of the wrist. Movement of the needle in an approximately longitudinal direction in such muscles is usually without effect on the form or amplitude of the action potentials recorded. Further experiments were carried out on the facial musculature. Here, the slightest movement of the needle tip alters the amplitude of the action potentials, and it is difficult to keep the needle sufficiently steady to record from a selected unit in the facial musculature for longer than ten seconds. A movement of less than ¼ cm. causes the motor unit action potential to reach an insignificant amplitude, but the latter is rapidly restored on withdrawal of the needle. It was observed that the average maximum amplitude of the motor units from facial musculature are not so large as those from the brachio-radialis muscle (Plate VIII, fig. 1).

In another experiment a normal volunteer had his left ulnar nerve blocked at the elbow-joint by 2 per cent. novocain containing 1 : 10,000 adrenaline. The needle electrode was inserted into the flexor carpi ulnaris muscle, and its position confirmed by stimulation, just previous to injection. During the course of the injection there were irregular outbursts of motor unit action potentials when the wrist was flexed. Immediately following the injection the patient was told to flex and extend the wrist at approximately one second intervals. The number of recorded action potentials rapidly diminished as the anæsthetic took effect (with increasing loss of pain sensibility in response to pin-prick over the hypothenar eminence). Sixty seconds after the injection the time-base tracing on the oscilloscope was only disturbed for approximately half its length during a maximum voluntary flexion effort at the wrist. Within seven minutes no electrical activity could be recorded from the muscle either at rest or in response to a maximum voluntary effort. Cautious movements of the needle point followed by stimulation to determine its position were then made. Again no action potentials were recorded either at rest or when flexion of the wrist was performed as long as the electrode remained in flexor carpi ulnaris. The movement of the needle point within the muscle was followed by an outburst of motor units of the "needle insertion" type, however, on each occasion. The needle was now moved in numerous directions and the effect of maximal wrist flexion noted. Following each movement of the needle its position was determined by stimulation. No electrical activity was recorded until the needle was within 1½ to 2 cm. of the muscle sheath in the direction of the wrist flexor muscles supplied by the median nerve (judged by resistance to the needle point and the subsequent result of stimulation), and then only a ruffling of the time-base tracing occurred (Plate VIII, fig. 2). No discrete motor unit action potentials were recorded until the muscle sheaths were pierced and the muscles of median distribution entered. From this experiment and others of a similar nature (including records from the interossei) it may be concluded that no discrete action potentials are recorded from neighbouring human muscles during their maximal contraction when a concentric needle electrode is employed to sample action potentials.

It can be shown on theoretical grounds that the action potential of a motor unit can give rise to a recordable impulse for a distance of the order of 4 cm. The discrepancy between this distance and those actually recorded, ¼ to 2 cm., may be explained by the fact that the needle employed has directional properties as demonstrated above. The rapid diminution of the action potential will be due not so much to distance as

to the fibres approaching or crossing the plane at the bevel of the needle. The difference between the muscles nevertheless suggests that the motor unit in brachio-radialis contains more fibres than in the facial muscles and thus produces a larger action potential. This is in accord with the suggestion of Hoefer and Putnam who believe that the variation in amplitude of motor unit action potentials depends upon the variation in the number of their constituent muscle fibres.

(2) *Trunk Muscles.*

There are certain muscles which can be relaxed by voluntary effort either not at all or only with difficulty in the normal subject. For instance the facial musculature, the tongue, the intrinsic muscles of the larynx, the scalenus anterior (and other neck muscles) and the abdominal musculature come under this heading. The face and tongue musculature have normally a resting "tone" of motor unit origin but partial relaxation can be achieved—at least completely for a short distance around the point of the needle—by concentrated effort and preliminary adjusting movements. During inspiration there is a shower of motor unit action potentials from the scalenus anterior and from the abdominal musculature; these die away to a minimum during expiration but are only with difficulty abolished when the breath is held. The laryngeal muscles cannot be relaxed completely in the normal subject; every breath in or out causes an outburst of action potentials, and even when the breath is held with the glottis open or closed a constant stream of action potentials are recorded. Contrary to expectation the sacro-spinalis muscles (thoracic and lumbar) are easily relaxed with satisfactory positioning but it has proved impossible to maintain relaxation of the cervical musculature with the exception of the trapezius muscle.

In general the amplitude of the action potentials recorded from the face, tongue and intrinsic laryngeal musculature is smaller than that recorded from limb or larger trunk muscles. In all groups, however, mono-, di-, tri- and polyphasic action potentials have been recorded although as in the case of limb musculature the commonest form of action potential is mono- or diphasic. These findings are in further confirmation of the work of Hoefer and Putnam who believe that the amplitude of a motor unit action potential is directly related to the number of muscle fibres of which it is composed.

(3) *The Effect of Prostigmin.*

In support of the conception that motor units are composed of single groups of closely approximated muscle fibres (Denny-Brown and Penny-

backer, 1938) we have obtained some observations on fasciculating muscles.[1] Two normal volunteers were each given 2·5 mg. of prostigmin and 1·0 mg. of atropin subcutaneously; this led to fascicular twitchings which reached their maximum at the end of half an hour (about 2 contractions a second in the brachio-radialis). They involved the voluntary muscles throughout the body and were visible through the skin as scattered intermittent contractions of isolated areas. The fasciculations appeared to involve long (up to 4 cm.) narrow (¼ to ½ cm.) bands of muscle fibres. Electromyographic recordings were made by inserting the needle electrode into a fasciculating bundle of the brachio-radialis muscle, and the action potentials recorded were found to be in no way different from those obtained in the normal voluntarily contracting muscle. Movement of the electrode as described above also caused the same variation in amplitude of the action potentials when moved through a similar distance, and there was no change in the shape of the spike when the needle was moved.

The question whether the point of action of the drug is peripheral or central was established by cautiously injecting 2·5 mg. of prostigmin intravenously into a volunteer who had already received 1 mg. of atropin half an hour previously. The vascular supply to the left arm was occluded by a "blood-pressure" cuff maintained at just above systolic pressure. Fasciculation appeared in three minutes throughout the limb and trunk musculature with the exception of the muscles below the point of vascular occlusion. A sensory test showed no gross alteration in cutaneous sensibility below the point of occlusion and it was noteworthy that, while at the height of the fascicular activity the patient complained of weakness of his limbs and inability to open his eyes, the left hand grip to the patient's surprise was "as strong as normal" and certainly much stronger than that of the right side. This experiment demonstrates that prostigmin acts peripherally and probably at the neuromuscular junction. Harvey *et al.* (1941) have already shown by other methods that prostigmin probably produces its effects by a distortion of normal neuro-muscular transmission. It might have been expected that each muscle fibre would respond independently to the effects of prostigmin, but this is not so, for electromyographically the action potentials resemble those of motor units and the appearance through the skin is that of the independent contraction of muscle "fasciculi." The work of Masland and Wigton (1940) has shown that the fascicular twitching observed after prostigmin is associated with antidromic impulses which can be recorded from the ventral roots and

[1]We have used the term "fasciculation" in the sense in which it was used by Denny-Brown and Pennybacker (1938).

they have also shown that the impulses are not caused by the mechanical contraction of the muscle fibres. It may be suggested therefore that the resemblance of fasciculation to motor unit activity is due to a peripheral antidromic impulse spreading throughout the motor unit and causing the whole to twitch.

Further evidence that the action potentials recorded from certain types of fasciculating muscle are indistinguishable from motor unit action potentials was furnished in the following case:—

L.A.C. T. P., of the R.A.F., aged 35, had acute anterior poliomyelitis as a child, involving muscles in both the upper and lower extremities on the right side. Apart from some weakness of the limbs on the right side as compared with the left, he was well until June, 1943, when the affected limbs began to get weaker and he complained of pain in his right shoulder. On examination on October 29, 1943, there was fasciculation in his right deltoid, pectoralis major, brachio-radialis and triceps muscles when they were apparently completely relaxed. The fasciculations appeared as twitchings of isolated bands of muscle about ¼ to ½ cm. in diameter and up to 7 cm. in length, and in this case were clinically in no way different from those produced by prostigmin. Electromyographic recordings from his brachio-radialis muscle, apparently completely relaxed, revealed a constant succession of action potentials indistinguishable from those of motor unit activity. Mono-, di-, tri- and occasional polyphasic action potentials were recorded, similar to those obtained from a normal muscle. Occasionally synchronous firing of two motor units close to the needle point was observed for as long as 5 seconds, simulating very polyphasic units, but their true character was eventually revealed for after a short while a slow phasic change occurred and the discharges became asynchronous. When the point of the needle was moved to ¼ to ½ cm. at right angles to the axis of the muscle fibres the action potentials waxed and waned as described in the case of a normal contracting muscle.

These findings indicate that the unit or group of contracting fibres in such cases gives rise to an action potential which is indistinguishable from that of a motor unit, an observation already made by Denny-Brown and Pennybacker. In addition the visible contraction seen through the skin is similar to that which might have been predicted when a contiguous group of about 300 to 400 muscle fibres of 70 to 100 μ in diameter contract simultaneously. Thus indirectly these observations support the contention that the muscle fibres composing the majority of motor units in limb musculature consist of single discrete groups of contiguous muscle fibres.

(4) *Discussion.*

The findings recorded above make it probable that the majority of motor units in human voluntary musculature are made up of single discrete groups of contiguous muscle fibres.

The variations in amplitude of the action potentials on slight movement of the needle electrode are due to its marked directional properties.

This explains the puzzling variations in amplitude during extended periods of recording noted by other workers using similar methods (Lindsley, 1935). In this connection we observed a slight decrease in the amplitude of a single diphasic action potential spike after it had been sustained for five minutes; the original amplitude was immediately restored, however, by withdrawing the electrode slightly.

Eccles and Sherrington (1930) have shown that there is a spectrum of fibre sizes in a motor nerve which has been deprived of its sympathetic and sensory components. This observation suggests that the motor unit is composed of a varying number of muscle fibres and our observations that the maximum amplitude of motor unit action potentials varies throughout a given muscle supports this conclusion and is in harmony with the suggestions of Hoefer and Putnam.

Clark (1931) has shown that motor units are composed of varying numbers of muscle fibres in different muscles. In the cat's soleus, for instance, he found a motor unit to consist of about 120 fibres and in the extensor digitorum longus muscle about 165 fibres, and he thinks it probable as the results of tension experiments that the soleus motor unit consists of 300 to 400 muscle fibres. From these findings Clark argued that muscles responsible for delicate movements such as the eyes and intrinsic muscles of the hand should have relatively fewer muscle fibres composing the motor unit as compared with muscles having less precise actions. Our observations on the differences between the action potentials recorded from the larynx, tongue, and particularly the face musculature and the brachio-radialis muscle, support Clark's contention.

(5) *Summary.*

(1) No electrical activity can be recorded from a voluntary muscle which is completely relaxed.

(2) No electrical activity can be recorded from a limb muscle, the motor nerve to which is blocked by local anæsthetic even though surrounding muscles are contracting strongly.

(3) It is possible to relax the majority of voluntary muscles without difficulty. Muscles which cannot be completely relaxed are the neck muscles excluding trapezius, and the intrinsic muscles of the larynx. Among those difficult to relax are the tongue, face and abdominal musculature.

(4) Motor unit action potentials vary in amplitude and duration in different parts of the same muscle.

(5) The average size of a motor unit action potential is greater in a

limb muscle (brachio-radialis) than in the face, tongue and laryngeal musculature.

(6) Motor unit action potentials from the muscles sampled vary in amplitude from 100 microvolts to 1 millivolt and duration from 5 to 10 milliseconds.

(7) Motor unit action potentials are most commonly mono- or diphasic, but triphasic and polyphasic action potentials are seen in all voluntary muscles.

(8) The concentric needle electrode has marked directional properties. Its normal recording range is limited to 1 to 2 cm. opposite the bevel.

(9) During a slight voluntary contraction 1 to 2 repetitive action potentials are recorded with rates of between 5 to 10/sec. As the tension increases the frequency of the action potentials may increase (max. recorded frequency 50/sec.) and more action potentials appear until with a powerful contraction the sweep on the oscilloscope is disturbed throughout its length by irregular spikes 1 to 2 millivolts in amplitude and 5 to 20 millisecs. in duration.

(10) The findings recorded are consistent with the view that a motor unit in human voluntary muscle consists of a single discrete group of contiguous muscle fibres.

IV.—Muscle Tone in Relation to Motor Unit Action Potentials.

(1) *Introduction.*

In the course of a discussion on muscle tone at the International Neurological Congress at Berne in 1931 Sherrington suggested that the word "tonus" should be abolished. Cobb and Wolff (1932) have reviewed the twenty-three papers presented at the Congress and point out that under the term "muscle tonus" were included such specific mechanisms as the standing reflex, postural reflex and righting reflex. These terms, they suggest, are more accurate, and they believe therefore that the word "tonus" should be applied only to smooth muscle where its meaning is more specific. McKinley and Berkwitz (1933) have investigated the subject by means of electromyographic recordings from a number of limb muscles of normal subjects elaborating the previous work of Wacholder and Altenburger (1927). They conclude that muscle "tonus" as usually assessed clinically is a very complicated mechanism. They suggest that, in the case of a stretched muscle when no action potentials can be recorded, the resistance or "tone" exhibited is due to the elasticity of the muscle fibres. They also draw attention to the work of Weigeldt (1922) who demonstrated

that the elasticity of muscles varies in pathological states. McKinley and Berkwitz state that they cannot explain some of their observations on the assumption that proprioceptive impulses resulting in spinal reflexes are responsible for tone as assessed clinically. In two of their tests (passive flexion and extension of a relaxed upper extremity) the first action potentials appeared in the muscles undergoing relaxation rather than in those being stretched. In other tracings, however, the initial action potentials were first observed in the muscle undergoing stretch and in these cases the "tonus" or resistance might in part be explained as the manifestation of a stretch or myotatic reflex. But even in these cases there were several examples in which motor unit activity occurred in the relaxing muscles immediately after the proprioceptive reflex action potentials had appeared. They suggest that the rôle of voluntary or higher reflex mechanism in producing fluctuations in muscle tone cannot be disregarded. They were quite sure that their subjects were completely relaxed when resting because of the absence of motor unit action potentials. During passive movements relaxation, they believe, depends on the "physiologic make-up" of the subject. They tentatively put forward the explanation that afferent impulses entering the nervous system during movement tend to set up a series of reflexes and a volitional inhibition of this type of response in an attempt to keep the arm relaxed results in irregular nervous overflow and motor discharge.

Hoefer (1941) also demonstrated that no action potentials can be recorded from voluntary limb muscles at rest even though they may be under a slight tension. Further, action potentials could not be recorded from spastic limb muscles at rest, but on the slightest movement there was a vigorous outburst of activity. He clearly showed that the clinical concept of tone in skeletal muscle is not covered by postural myotatic reflex regulation and demonstrated that this mechanism only comes into operation when muscles are stretched at a considerable speed such as during the elicitation of a tendon reflex.

Holmes (1939) has stated that "to the clinician, tone generally means the constant slight tension characteristic of healthy muscle which offers a steadily maintained resistance to stretching; it is recognized by the resistance experienced when the limbs are moved or displaced passively."

As the above critical review of the literature demonstrates, there is no universally accepted definition of the words "muscle tone." For the sake of accuracy it might be best to drop the term altogether, but this is hardly practicable since the word has gained universal usage and has no convenient substitute.

(2) *Methods.*

Taking Holmes' broad definition of "muscle tone" as a basis, therefore, we have compared the electrical activity recorded from extremity muscles with the mechanical resistance experienced when joints were moved or displaced passively.

(3) *Observations.*

To determine the motor unit activity which results from passive displacement of a joint in normal persons, needle electrodes were inserted into the extensor carpi radialis longus muscles of ten subjects. The forearms were placed on a waist-high table with the wrists hanging loosely over the edge. It was explained to each subject that he was to relax as completely as possible and that once the electrode was in place he would feel no pain. The wrist was then rapidly fully flexed and extended by the examiner. In all but one case it was possible to persuade the patient to relax so that no motor unit activity was recorded from any of the points sampled in the muscles during this manœuvre, and indeed, in three cases no persuasion was necessary. In two subjects motor unit activity appeared when the examiner was rough in handling the wrist or appeared too enthusiastic in his manner of approach. In one individual (a "nervous type"), motor unit activity appeared whether the wrist was flexed, extended or motionless and it was impossible to persuade him to relax so that no motor unit activity was recorded although the greatest activity was seen when the wrist was being moved either up or down. Normal myotatic reflex responses could be elicited in all of the subjects by tapping over the brachio-radialis (supinator) tendon sharply with a reflex hammer. The percussion resulted in an outburst of motor activity which varied quantitatively with the weight and swiftness of the blow as well as from subject to subject. Following these procedures the individuals were examined clinically but the tests were limited to palpation of the forearm muscles and passive displacement of the wrist. In two of the three normal subjects in which the passive wrist movements were unaccompanied by motor unit activity at any time, the examiner reported "reduced muscle tone such as might be encountered in a patient with a cerebellar lesion." The remaining subjects were reported to have normal "tone." Parallel findings were observed when either the calf or tibialis anterior muscles were employed under similar conditions. From these observations we concluded that "tone" of motor unit derivation in normal limb musculature subjected to passive displacement depends on the emotional, or conscious level, thresholds of the individual.

It may be objected that our methods of recording from limited portions of the muscles determines the absence of recorded motor unit activity. For this reason we had recourse to surface electrodes and multiple channel recording with an electro-encephalogram inkwriting apparatus, employing "Grass" amplifiers. Our observations in the ten subjects referred to above were confirmed. The work of Hoefer (1941) is interesting in this connection for he has shown how few motor unit action potentials can be recorded from the antigravity muscles during maintenance of the erect posture in the normal human subject. We have confirmed Hoefer's observations and in text-fig. 2 is shown a tracing from the thigh and calf muscles when one of us was standing in a "relaxed manner." Hoefer suggests that in such postures as standing, tissue elasticity is always fully made use of before motor unit activity is called into play. Thus in the normal subject muscle "tone" in limb musculature is dependent only in part on motor unit activity, and, moreover, the amount displayed varies from subject

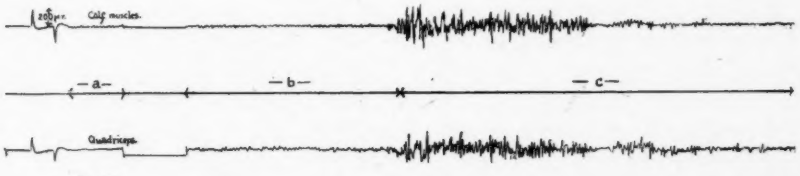

FIG. 2.—Simultaneous tracings from calf and quadriceps muscles, (*a*) subject sitting, (*b*) subject standing in a "relaxed attitude," (*c*) regaining equilibrium after swaying forwards slightly.

to subject and is related to individual emotional and conscious levels of activity.

In view of these findings in normal subjects it was to be expected that in our observations in pathological states it might be equally difficult to relate motor unit activity to the degree of muscle tone assessed by palpation and passive displacement.

For instance:—

L/Cpl. G., aged 25, sustained a fracture dislocation of his 6th cervical vertebra during a football match on September 11, 1943. The injury resulted in immediate paraplegia below a segmental level of C7. He was seen at a Military Hospital twenty-four hours after the injury, which proved, at autopsy four days later, to have severed his cord completely. At this time a clinical examination showed a complete paralysis of all muscle below C7 and complete sensory loss affecting all modalities. There was priapism, the left cremasteric reflex was present, and there was a slow plantar flexion response to stimulation of the sole of the foot. Both knee and ankle jerks were absent. Palpation and passive displacement of the lower

extremities showed no spasticity, but a number of clinicians agreed that the "muscle tone" was above normal. Immediate comparisons were made with normal subjects and with the intact muscles of the patient's shoulder girdle, and the increase of "tone" was confirmed. Numerous electromyographic recordings were made from the chief muscle groups in the lower extremities. No motor unit action potentials were apparent (apart from those associated with the insertion of the needle) in response to palpation or passive displacement at the various joints. Indeed, no motor unit activity was elicited in the appropriate muscles in response to blows with a percussion hammer over the patellar or Achilles tendons. Vigorous motor unit action potential outbursts, however, appeared in the intrinsic foot muscles on stroking the sole of the foot. The outburst was approximately proportional to the strength of the stimulus and was clearly of a reflex nature, for the area of the skin stimulated was not necessarily over the muscles from which the responses were obtained. Moreover, there was an appreciable delay between the application of the stimulus and the motor unit outburst. Thus in this case, although, clinically, "tone" was found to be above normal, the increase was not due to reflex motor unit activity. It seems not improbable that there was an increase in the muscle blood volume in the lower extremities due to vasomotor paralysis and that this was related to the increased "tone," for Riddoch (1917) has observed that dependent limbs swell quickly in the early stages following spinal cord injury.

To give another example:—

A.C.1 C. S., aged 19, was admitted to a Military Hospital complaining of headaches, vomiting and dimness of vision. He was found to have signs of increased intracranial pressure and a ventriculogram suggested a right-sided posterior fossa lesion. At operation a tuberculoma was excised from the right cerebellar hemisphere together with the overlying cortex. For a number of days following the operation he presented all the signs of an acute right-sided cerebellar lesion. These gradually subsided in the following weeks and at the time of his discharge, five months later, it was only possible to detect abnormal signs referable to the cerebellum on the most careful clinical examination. The right arm exhibited typical cerebellar atonia two weeks after operation and electromyographic recordings were made from the extensor carpi radialis muscle. No motor unit action potentials were recorded in response to palpation or passive displacement of the arm. The usual outburst, however, accompanied percussion over the tendon with a reflex hammer. In response to these tests the patient behaved in no way differently from many normal subjects, and yet clinically "tone" was undoubtedly diminished in the right arm as compared with the left. Recordings were next made from the anterior portions of the deltoid muscles when the arms were held horizontally outstretched and the eyes closed. There was a steady decrease in the number of action potentials recorded from the affected side as the arm slowly descended from the horizontal.

Holmes has already drawn attention to the best methods of testing for cerebellar atonia, all the methods advocated depending upon changes in *active* movements of the limb. He says, "a lack of tone can often be recognized by handling the limb, but the essential fact is that the hypotonic limb can be displaced with unnatural ease from any position determined by the contraction of its muscles; its posture is not adequately

fixed by their tonic contractions." It is thus apparent that, in relation to the cerebellum, muscle "tone" has a dynamic rather than a passive connotation.

There is no doubt that a constant stream of motor unit action potentials can give rise to an increase of "muscle tone" as, for instance, in spastic hemiplegic states or Parkinsonism, although these two conditions present striking differences electromyographically.

Pte. R., a left-handed man aged 33, on April 23, 1943, sustained a compound comminuted fracture of the skull on the left side. A cerebral abscess developed and was drained, and his wound subsequently healed satisfactorily. He was, however, left with a severe right-sided spastic hemiplegia with minimal sensory loss of a cortical type. On August 20, 1943, needle electrodes were inserted into the right calf muscle, the limb having been put, as far as possible, into a position of rest, that is with the knee and ankle partially flexed. There was the usual outburst of action potentials on insertion of the needle, but this was followed by electrical "silence." Gentle palpation of the calf muscle immediately evoked an outburst of motor unit action potentials and even movements of the needle were effective in so doing provided they produced visible deformation of the muscle. The slightest stretching of the muscle produced a rhythmic outburst of motor unit action potentials even though clonic movements were not visible. Brisk dorsiflexion of the ankle with maintenance of pressure produced a large rhythmic outburst of motor unit action potentials which were accompanied by the usual clonic movements. If pressure was maintained on the sole of the foot the clonic movements died away and the action potentials lost their rhythmic character and became indistinguishable from those observed during a sustained voluntary contraction. This phase only lasted for a short while before electrical "silence" supervened, and continued until the ankle was moved again. Parallel findings were observed with the needle in the brachioradialis muscle, save that there was a continuous stream of motor unit action potentials on stretching the muscle in place of rhythmic outbursts. It is of some interest that during sleep the extreme spasticity in this case was markedly decreased though not abolished.

It is clear that the spasticity or increase of "tone" in this case was due to motor unit activity. The "tone" was only manifest, however, in response to stretch; a myotatic reflex with an extremely low threshold. During rest there was no electrical activity.

Parkinsonism presents a different picture in that the spasticity or increased "tone" due to motor unit activity is present whether the muscle is being stretched or is in a position of relaxation.

Mr. K., aged 78, a printer by occupation, complained that for the last nine months he had been worried by a tremor which had started in his left arm and now involved the right, and that the movements kept his wife awake at night. When examined on January 27, 1944, he presented a typical picture of Parkinsonism, the tremor being most marked in the left upper extremity. Needle electrodes were inserted into the right extensor carpi radialis muscle. There was a constant stream of motor unit action potentials which were not under voluntary control, and additional units were recorded at each contraction cycle of the tremor. Efforts

were made to place the arm in such a position that no motor unit action potentials were recorded. This was not possible. However, the additional motor unit activity related to the tremor could be abolished for short periods, during which the limb was being moved passively. Soon after a fixed position had been adopted or a voluntary movement attempted, the additional rhythmic outburst of motor unit action potentials recommenced and continued in varying degrees depending upon the position of the limb. It was not possible to obtain electrical "silence" even after the tremor had been temporarily abolished by one or two forceful movements followed by fixation of the limb. The number of motor unit action potentials was, however, diminished. Our findings confirm those already described by Ingebrigtsen (1938).

Further examples of abnormal muscle "tone" and concomitant electrical activity were afforded by the following cases:

Myotonia congenita.—Pte. J. M., aged 19, was admitted to a Military Hospital on July 28, 1943, complaining of stiffness of the legs. On examination he appeared to be an abnormally well-developed boy with a spastic gait which improved with exercise. The limb muscles were hypertrophied and their power was good, but relaxation of the hand grip was slow and a well-marked percussion myotonia could be demonstrated. On passive movement of any large joint the muscle tone was increased in both flexor and extensor muscle groups; if the movement was repeated a number of times the "tone" gradually decreased and approximated to normal. "Tone" was also said to be increased when the muscles were palpated. There was a clear family history of myotonia congenita in this case.

Insertion of the needle electrode into the extensor carpi radialis longus muscle evoked the outburst of an intense shower of high frequency motor unit action potentials which sounded like low-pitched musical notes. These continued for as long as twenty seconds and were followed by smaller, sharper action potentials, resembling those of fibrillation and lasting for about five seconds, before electrical silence supervened. These action potentials could easily be provoked again by palpation or percussion of the muscle close to the needle point, and followed a similar course. Voluntary contraction produced a shower of motor unit action potentials of very high frequency which were again followed by fibrillation-like action potentials during the period of relaxation (Plate VIII, figs. 3 and 4). During passive flexion or extension of the wrist there was an outburst of action potentials resembling those evoked by the insertion of the needle but lasting for a shorter time. During these manœuvres, however, it was impossible to exclude small movements of the needle point which in turn might have been responsible for the appearance of some of the action potentials. In this case we were able to confirm the existence of "muscular myotonia" and "after spasm" described by Denny-Brown and Nevin (1941) as occurring in myotonia congenita. This case further demonstrates the relationship between muscle "tone" and motor unit activity; in this particular subject changes at the neuromuscular junction were responsible for the clinical and electrical changes observed.

Myasthenia gravis.—Quite another picture is afforded by the following case, although once again abnormalities at the neuromuscular junction are most probably the cause of the disease.

L/Bdr. F., aged 43, was admitted to a Military Hospital on February 9, 1943, complaining that for the last five months he had found it increasingly

difficult to chew his food and keep his eyes open during the latter part of the day. On examination he presented a typical picture of myasthenia gravis. On March 15, 1943, a needle electrode was inserted into his right masseter muscle and the patient told to clench his jaw tightly; the action was accompanied by a large outburst of motor unit action potentials. Within thirty seconds, however, the number of action potentials recorded was diminishing rapidly and it was now possible to observe individual motor units. Within a further sixty seconds there was electrical "silence," the jaw hanging open, the muscles supporting it apparently toneless and the patient quite unable to close his mouth. It was particularly noticeable during the latter part of the examination that the amplitude of the individual motor unit action potentials decreased before they disappeared from the screen of the oscilloscope. This observation, although not absolutely conclusive (for the electrode may have shifted its position relative to the motor unit in question in the relaxing muscle), is suggestive of a progressive decrease in the number of muscle fibres contracting within the motor unit. This observation is in accord with the work of Harvey *et al.* (1941). Following the administration of prostigmin subcutaneously the tone of the masseter muscle rapidly increased and normal motor unit activity was re-established. In this case there was steady decline in muscle "tone" paralleled by a steady decrease in motor unit activity.

Peripheral nerve interruption.—Axonal interruption of a peripheral nerve is always followed by a loss of tone in the denervated muscles. This loss, however, is difficult to explain in relation to electrical activity as the following case demonstrates.

Pte. G., aged 28, on July 30, 1943, had his right radial nerve completely interrupted by a mortar shell fragment. On August 24, when examined at a Military Hospital, the wasting of the affected muscles was only slight but they were flabbier than the corresponding muscles on the normal side. Moreover, passive flexion of the wrist was possible to a greater degree on the affected as compared with the normal side. Needle electrodes were inserted into the wrist extensor muscles of both sides, with the arms resting comfortably on a table. No electrical activity was recorded from the normal muscles save that aroused by the insertion of the needle. From the abnormal side, however, a profuse outburst of fibrillation action potentials followed the insertion of the needle and a continuous succession of similar action potentials were recorded as long as the needle remained in the muscles (*vide infra*). On August 27, 1943, hypodermic needles containing thermocouples at their tips were inserted into the depths of the forearm extensor muscles at approximately the same relative positions on the two sides. There was an average difference in temperature of 2½° C. between the two sides, the affected side being the cooler.

In the light of the work of Barcroft and Millen (1939) this finding suggested that there was possibly a diminution of blood flow through the denervated muscles; other workers, however, have reported that the blood flow through denervated muscles is increased (Wilkins and Eichna, 1941). Recently denervated muscle, when severed with a knife at operation, retracts in a manner comparable to normal muscle so that the diminution of "tone" is unlikely to be related to a change in the elasticity of the muscle fibres, although small changes are not excluded by this observa-

tion. There is another factor, however, which must be taken into account. Wells *et al.* (1938) have shown that intramuscular pressure is affected independently by several factors, of which the most important are: the tightness of the fascia, the amount of intravascular and extravascular fluid present and the components of contractile force of the muscle. Intramuscular pressure cannot be used as an index of muscle tonus unless all of these factors are controlled. It may be, therefore, that the diminution in tone of a denervated muscle is due in part to the mere reduction of muscle fibre bulk within the fascial sheath consequent on denervation atrophy.

Ischæmic fibrosis.—Weigeldt has demonstrated that the elasticity of muscle varies in pathological states and it may be that this factor plays a part in alterations in muscle tone following denervation. Rheological properties in general certainly have a rôle in this connection. For example:—

> Pte. E. S., aged 28, as the result of a motor cycle accident on July 20, 1943, sustained a head injury and a right brachial plexus injury in addition to a deep laceration in his right axilla which necessitated the tying of his brachial artery close to its origin. On examination at a Military Hospital on October 20, 1943, he had weakness of the muscles of median and musculo-cutaneous distribution. His right biceps muscle felt rubbery in consistency, and passive displacement suggested an increase in "tone." The muscle at first was thought to be contracting in some measure since flexion at the elbow remained a powerful movement. Electromyographic recordings showed that the flexion of the arm was not being carried out by the biceps, for in no part of the muscle could motor unit action potentials be recorded during flexion of the elbow. Moreover, only in a few positions in the upper third could fibrillation action potentials be obtained. The muscle was hard to penetrate with the needle and in some positions was definitely "gritty." Apart from the few fibrillation action potentials in the upper third, the muscle was electrically "silent." It had evidently undergone some forms of ischæmic fibrotic change.

This case illustrates how such a change in constitution of a muscle can be defined in terms of change in muscle tone when the latter is judged by palpation and passive displacement.

(4) *Conclusions.*

As the result of our findings in the above quoted and other similar cases, we suggest that muscle "tone," when defined as a resistance experienced when the limbs are moved or displaced passively (*vide* Holmes, 1939), although an extremely complex phenomenon is capable of analysis into a small number of relatively simple factors which can, of course, be further subdivided into more specific entities. Table I summarizes the result of our attempt at such an analysis:—

TABLE I.

Group	*Factor*	*Clinical Group*
1	Intra- and extra-vascular fluid within the muscle sheath	(*a*) Increased tone due to increase of blood volume, *i.e.* vasomotor paralysis
		(*b*) Decreased tone due to decrease of blood volume, possibly as the result of denervation
2	Rheological properties of the muscle	(*a*) Increased tone, due to cold
		(*b*) Decreased tone, due to warmth and denervation (reduction of muscle fibre bulk within the fascial sheath)
3	Motor unit activity within muscle (nervous system intact)	(*a*) Increased tone, hyper-reflexia type
		(*b*) Decreased tone, hypo-reflexia type
4	Motor unit activity within muscle (nervous system damaged or diseased)	(*a*) Increased tone, due to lesions of cortico-spinal pathway (spastic hemiplegia)
		(*b*) Increased tone, due to lesions of basal ganglia (*e.g.* Parkinsonism)
		(*c*) Increased tone. Changes at the neuro-muscular junction (myotonia congenita)
		(*d*) Decreased tone. Lesions of the cerebellum
		(*e*) Decreased tone. Changes at the neuro-muscular junction (myasthenia gravis)

V.—THE ACTION POTENTIALS FROM DENERVATED MUSCLES.

(1) *Introduction.*

Remarkably few observations have been published on the action potentials from denervated voluntary muscle in Man. The first notable contribution in the literature is by Proebester (1927), who described spontaneous irregular action currents of a frequency around 110_{σ} and which he obtained, at rest, from the weak left biceps muscle of a 13-year-old boy who had probably suffered a traumatic brachial plexus birth lesion. Recordings from normal muscles of the opposite side of the body showed no such action potentials. He also reports that action potentials of a similar type can be obtained from cases of long-standing post-poliomyelitic paralysis. Proebester considered that these action potentials represented a periodic discharge from the central nervous system. It is, however, more probable that they represented the electrical counterpart of fibrillation of denervation, for they differed in no respect from the action potentials led off from fibrillating muscle in experimental animals. The next mention of the action potentials from denervated human muscle is made by Denny-Brown and Pennybacker (1938) who used concentric needle electrodes and a Matthews' oscillograph for recording. They have summarized the literature relating to the action potentials of fibrillation from denervated muscle in experimental animals (mammalian) and conclude that

"the fibrillation of muscle undergoing atrophy as a result of denervation is due to periodic rhythmical twitch excitation of each muscle fibre sensitized by neural atrophy. The source of excitation would appear to be small amounts of acetylcholine in the normal circulation." They proceed to state that such fibrillation can be observed clinically in man when the subcutaneous tissue is unusually thin and that intact sensory nerves do not influence the phenomenon. They give tracings which indicate that action potentials in no way differing from those obtained from completely denervated muscles in animals can be obtained from patients suffering from amyotrophic lateral sclerosis, and facial palsy with partial recovery. They also show a tracing from the mylohyoid muscle "of a patient suffering from wasting of the musculature of the tongue due to syringomyelia," which again differs in no essential way from the action potentials obtained from the completely denervated gastrocnemius muscle of the cat, a tracing of which is also given.

(2) *Observations.*

Time-course.—The time-course and appearance of fibrillation action potentials in the brachio-radialis and extensor carpi radialis longus muscles in Man following denervation are described elsewhere for a single experimental case. Briefly, following denervation, insertion of the needle electrode provoked a short outburst of motor unit action potentials (motor unit action potentials of the "insertion" type). Such activity could be provoked for a period of eighteen days. Sixteen days following denervation a further type of action potential made its appearance on insertion of the electrode, 1 to 2 millisecs in duration and up to 100 microvolts in amplitude. These action potentials (fibrillation action potentials of the insertion type, Plate VIII, figs. 5 and 6) lasted appreciably longer than the motor unit outburst. Eighteen days following denervation the outburst of fibrillation action potentials following the insertion of the needle was succeeded by a series of repetitive spikes, varying in frequency from 2-20/sec., of a similar nature; spontaneous fibrillation action potentials (Plate VIII, fig. 7) and such activity continued uninterrupted until re-innervation took place. Although the subject was thin, no movements were seen through the skin and he was aware of no subjective sensation related to the recorded activity. There was no demonstrable sensory change. Further observations have been made in over 100 cases of peripheral nerve lesions investigated at a Military Hospital, and in no case of proved axonal interruption have we failed to find repetitive action potentials indicative of fibrillation. The muscles examined have included those of the face, tongue, larynx, neck, trunk and

upper and lower extremities. We were able to confirm the observations of Proebester that the activity gives rise to no subjective sensation. In the tongue it is possible actually to see the fibrillations but they are not visible in the muscles covered by intact skin. The technique was similar to that employed in the investigation of action potentials from normal muscle.

With experience, a fibrillation action potential can readily be distinguished from a motor unit action potential by the sound which it produces. It is heard as a sharp click, while the motor unit action potential is heard as a low-pitched sound from the loudspeaker. On occasions, depending upon the relation of the bevel of the needle to the contracting unit, it may be difficult to distinguish the action potential by differences in sound alone. In such cases, notice is taken of the rhythmic quality of the fibrillation action potential, and the fact that it is quite uninfluenced by efforts at contraction or actual contraction of nearby normally innervated muscle fibres. Rarely, as the result of a partial or slowly progressive nerve lesion, motor unit action potentials may discharge rhythmically and remain uninfluenced by attempt at, or actual, voluntary movement. In such cases the sound emitted by the loud speaker is characteristic of a motor unit and in addition, if care is taken to observe the type of action potential aroused on insertion or sharp movements of the needle point, it is comparatively easy to distinguish the type of activity present. In such cases a number of needlings should invariably be done and the point of the needle moved freely through the muscle in order to assess the condition accurately.

It was shown in our experimental case that denervated voluntary muscle in Man fibrillates in the same way as in experimental animals, and our observations on clinical cases have substantiated this finding. The time-course in Man, however, is different; in particular, the onset is much later. In one of our cases[1] electromyographic recordings were made from the affected muscles eighteen days following the injury.[2]

Flt./Sgt. D., aged 27, was admitted to a Military Hospital on September 25, 1943, sustaining a partial left brachial plexus lesion as the result of an air crash. He was unable to abduct his left arm at the shoulder-joint or to flex his left elbow. All other movements of the left upper extremity were present though weak.

Insertion of the needle electrode into both the left deltoid and biceps muscles

[1]In this and the following cases the muscles undergoing examination were warm or warmed at the time of insertion of the needle unless otherwise stated.

[2]We have recently had the opportunity of examining a number of cases of peripheral nerve interruption involving muscles of the extremities less than eighteen days after the injury. Our observations have paralleled those made in the case of experimental nerve interruption in Man.

present case when the needle was shifted to another point in the muscle a series of fibrillation action potentials was observed, two of which repeated in phase 20 millisecs apart over a period of eighty seconds; after this a slow phase shift took place and subsequently for brief periods the action potentials would again discharge synchronously, giving the appearance of a complex spike.

Tower (1939) has ventured the statement that there seems to be no reason why a muscle should not continue to remain a potentially contractile tissue indefinitely after denervation. We have evidence that fibrillation action potentials can be recorded from muscles denervated as the result of an attack of acute anterior poliomyelitis eighteen years previously. For example:—

Mr. B. D., aged 23, a laboratory technician, had an attack of acute anterior poliomyelitis at the age of 5 years. Paralysis involved the lower extremities, the right leg being more affected than the left. On examination at a Military Hospital on May 8, 1944, the right leg was found to be grossly wasted. The hamstrings and muscles below the knee were most affected, and the only movement possible below the knee was feeble flexion of the toes. There were no sensory changes. Needle electrodes were inserted into the calf, anterior tibial and peroneal muscle groups. From all these muscles repetitive fibrillation action potentials were recorded, although not from all positions of the needle point. It was also noticeable that the number of repetitive spikes recorded at each position of the needle point was less than in a recently denervated muscle. There were a number of places in all the affected muscles (to judge from the texture of the tissue when the needle point was moved) at which fibrotic changes had taken place. Motor unit action potentials were recorded from the flexors hallucis and digitorum longus muscles, but only sufficient to obliterate half the time-base tracing on the oscilloscope.

In complete nerve lesions.—Fibrillation action potentials can be recorded from a muscle the nerve to which has been partially interrupted. As already described it is usually quite easy to obtain relaxation of the muscle in which case all motor unit activity disappears; fibrillation action potentials can then be recorded unobscured. If, however, complete relaxation cannot be obtained, the nerve to the muscle can be blocked with 2 per cent. novocain solution containing 1:10,000 adrenalin, and the test repeated. For example:—

Sapper C., aged 28, was admitted to a Military Hospital on June 23, 1943, complaining that for four weeks previously he had noticed that his right hand grip was becoming weak. On examination there were weakness and wasting of the ulnar intrinsic muscles and indefinite impairment of cutaneous sensibility over the ulnar area and the palmar aspect of the thumb. A sweating test showed a small degree of hypohydrosis over the whole palm and medial aspect of the forearm. Both the sweating and sensory tests suggested that the lesion involved the C.8 and T.1 nerve roots rather than the ulnar nerve at the elbow. Confirmation of this hypothesis was obtained by electromyography. In the first instance all the intrinsic

provoked an outburst of fibrillation action potentials. The majority of these died away in one or two seconds leaving a small residue of fibrillation action potentials of one or two repetitive spikes. In addition to the fibrillation action potentials, insertion of the needle also provoked an outburst of motor unit action potentials; these were not so numerous as in normal muscles but they sufficed to make analysis of the sounds somewhat difficult. Two days later, electromyographic recordings from the same muscles showed no motor unit action potentials, but the fibrillation action potentials had increased in number.

In this case, therefore, motor unit action potentials could be provoked for at least eighteen days following denervation, and the onset of continuous fibrillation had commenced by the eighteenth day. These findings are very similar to those in our experimental case and the question arises whether the time-course of fibrillation is relatively constant in different individuals.

Further evidence on this point was provided by the following series of cases. Needle electrodes were inserted into the sacrospinalis muscles of 25 patients who had had laminectomies performed for prolapsed intervertebral disc. The needles were inserted on either side and approximately 1 cm. from the mid-line scar. A band of muscle at least 2 cm. wide, and of full thickness on either side of the scar, was found to be denervated following such operations. Motor unit action potentials were provoked by the needle point for twelve days following operation. Fibrillation action potentials were provoked by the needle point after ten days and repetitive fibrillation action potentials were present twelve days following operation. The time-course of the phases of electrical activity following denervation was thus shorter in the sacrospinalis muscles than in the limb musculature of our experimental case; although in the sacrospinalis musculature it proved to be remarkably constant from subject to subject. It was also observed that the average number and frequency of the fibrillation action potential spikes in the denervated sacrospinalis musculature four or more weeks after denervation was greater than in limb musculature denervated for a similar period (Plate IX, fig. 1).

Fibrillation action potentials are usually mono- or diphasic spikes which repeat rhythmically for a considerable period. For example:—

Pte. E. M., aged 26, as the result of a motor cycle accident on June 29, 1943, sustained a complete right musculo-cutaneous nerve axonal interruption. On August 24, 1943, a needle electrode was held rigidly in the same position in the right biceps muscle for a period of seven minutes. During this time two fibrillation action potentials were recorded unchanged in duration or amplitude, repeating at intervals of approximately one, and one and a half times a second respectively.

In other cases more complex spikes may occur, but they are probably due to a synchronous contraction of two or more muscle fibres for, in the

detection of fibrillation action potentials is far more difficult. The following cases illustrate this point:—

Case 1.—Gnr. G., aged 27, was admitted to a Military Hospital on March 26, 1943, complaining of progressive stiffness; weakness and wasting of the muscles of his hands. He intimated that his attention was first drawn to the condition six years previously when, during the cold winter weather, he could not straighten his left thumb properly and his left hand felt particularly stiff and weak. This weakness gradually spread to both hands and, in addition, his hands and the lower parts of his forearms gradually got smaller. On examination he had marked localized wasting of the intrinsic muscles of the hands and the distal thirds of his forearms. His feet were thin and highly arched but there was no obvious wasting of the intrinsic muscles and no involvement of the leg muscles. The clinical diagnosis was considered to be muscular atrophy of the "peroneal" type. Needle electrodes were inserted into the intrinsic muscles of both hands after warming and after the subcutaneous injection of 2·50 mg. of prostigmin (*vide infra*). No fibrillation action potentials were recorded in any position in the muscles after numerous needlings had been done.

Two possibilities exist to account for our failure to obtain fibrillation action potentials in this case. The disease process may have involved the muscle fibres and not the motor nerves; or the slow progress of the disease might have determined the degeneration of the denervated muscle fibres and their replacement by fibrous tissue. Unfortunately no biopsy could be obtained. The complaint of stiffness which the patient emphasized suggests fibrous tissue replacement. In another case the circumstances were quite different.

Case 2.—F/Lt. A. W. C., aged 30, was admitted to a Military Hospital on May 31, 1943, complaining of pain and weakness of his right shoulder. He gave the following history; he was quite well until December, 1942, when he began to get an ache in his right shoulder and round the base of the neck on the right side. A few weeks later he was told that his right shoulder was drooping. During the next two months the shoulder became flatter and weaker and the ache increased, and he was taken off flying duties. In February, 1943, he noticed a little numbness and tingling down the inner border of the right arm and hand and into all the fingers, the thumb remaining unaffected. The paræsthesiæ were particularly associated with swinging movements of the arm. The patient could think of no incident when his right shoulder might have been specifically subjected to trauma. On admission he stated that there had been no change in the condition recently. On examination his right trapezius, deltoid, supra- and infraspinatus, rhomboids and serratus anterior muscles were all weak and wasted. No other muscles were involved and no fasciculation was seen, although slow myotatic irritability was present in the affected muscles. There were no objective signs of sensory impairment, and the reflexes were equal on the two sides. The diagnosis was considered to be radiculitis. Needle electrodes were inserted into the affected muscles and moved into a number of different positions. No fibrillation action potentials were recorded. The motor unit activity, however, was reduced and was only sufficient to obliterate half the base line on the oscilloscope during a maximum voluntary contraction.

The absence of fibrillation in this case may be explained on the assump-

muscles of the hand were examined, but it was found that the patient could not relax sufficiently for an accurate assessment to be made. The median and ulnar nerves were therefore successively blocked with 2 per cent. procaine (block proved by a sensory test and attempts at voluntary movement) and the examination repeated. Fibrillation action potentials were obtained from all the intrinsic muscles of the hand including the small muscles of the thumb.[1] It was therefore decided to expose the right brachial plexus, and at operation a well-developed tendon of the scalenus minimus muscle was found to be compressing the lower trunk of the brachial plexus against the first rib. Both the C.8 and T.1 roots showed macroscopical evidence of pathological change at the level of compression.

The next case illustrates findings typical of those obtained in cases of slowly progressive peripheral nerve interruption.

F/Sgt. G. L. D., aged 23, was admitted to a Military Hospital on October 1, 1943. He was confused, disorientated and unco-operative as the result of a severe head injury occasioned by an air crash on September 22, 1943. He slowly recovered from his head injury and on October 12, 1943, examination showed that he had sensory loss and muscle paralysis corresponding to a lesion of C.3 to C.6 nerve roots. The deltoid and spinati were completely paralysed. The biceps and brachio-radialis muscles each gave only a flicker of contraction. The triceps and remaining muscles below the elbow could contract against resistance. In the deltoid and spinati muscles a few motor unit action potentials as well as fibrillation action potentials were evoked on insertion of the needle, but there were only six motor unit action potentials under voluntary control. A number of spontaneous repetitive motor unit action potentials, which did not vary in speed when the patient attempted to contract the muscles, were also recorded. Two days later only an occasional motor unit action potential was encountered on insertion of the needle, and only three normal motor unit action potentials, but there were still a number of repetitive motor unit action potentials uninfluenced by attempted movement. After this, examinations were made at weekly intervals for the next three months, when it was found that motor unit activity disappeared by slow degrees until on January 10, 1944, only one spontaneous repetitive motor unit action potential was recorded. In the partially affected muscles, there was a steady increase in fibrillation activity and decrease in motor unit activity accompanied clinically by a small loss of power. The condition remained stationary after January 10, 1944, clinically and electromyographically.

We have observed a similar series of events in a case of ulnar nerve lesion due to a through-and-through bullet wound in the middle of the arm. A few motor unit action potentials were recorded from the clinically paralysed abductor minimi digit muscle soon after injury, but they gradually decreased in number and finally disappeared, as a palpable neuroma developed at the site of injury.

In certain cases of muscle weakness and wasting where partial peripheral nerve (axonal) interruption is inferred as part of the disease process, the

[1]It is possible that the ulnar nerve might have been supplying a few fibres of those intrinsic muscles usually supplied by the median nerve, but the sensory and sweating tests made this interpretation unlikely.

tion that there was no denervation, but that a number of the nerve fibres were in a condition of reversible ischæmic block (*vide infra*), thus giving rise to the clinical picture. Alternatively, in addition to a reversible ischæmic block there may have been divided axons but so few in number that it was unlikely that the few motor units denervated would have been encountered unless an excessively larger number of needlings had been done. The clinical course in many cases of radiculitis is in favour of a pathological diagnosis of reversible ischæmic block. Unfortunately, in this case also, a biopsy could not be obtained, so the exact condition of the affected muscle remains in doubt.

The following case illustrates another condition which may give rise to difficulty in interpretation.

Case 3.—A.C.1 L. G. of the R.A.F., aged 36, was admitted to a Military Hospital on September 6, 1943. He was complaining of weakness and wasting of the muscles in his right leg. He gave the following history. He had known that his right foot was smaller than his left for the last twenty years for he had always had to put large pads into his right shoe to keep it on. He said that his attention was first drawn to the wasting of his leg at the medical board on the occasion of his call-up. He had not noticed it before. He put down the wasting to an injury at the age of 10. Recently, he stated, the leg had become weaker and the wasting greater. On examination the right foot was smaller and the right leg shorter than the left. There was some generalized wasting of all the muscles of the right lower extremity and also some weakness. There was specific wasting of the right calf muscles (2¾ in.) and some contracture of the Achilles tendon. The right ankle-jerk was absent. No sensory change was detected and no fasciculation seen. The condition was diagnosed as being the result of acute anterior poliomyelitis at an early age. Needle electrodes were inserted into all muscle groups of the right lower extremity after warming the limb, but no fibrillation action potentials were encountered in any position. If the clinical diagnosis was correct the absence of fibrillation action potentials suggests that the denervated muscle fibres had undergone a morphological change. The presence of a few denervated motor units again could be excluded for, as suggested in the previous case quoted, it would be necessary to do a very large number of needlings to exclude their presence.

In the case of experimental animals we have shown that the component muscle fibres of motor units are not scattered throughout a muscle. The following case suggests that this is also the case in Man.

Case 4.—A.C.2. M., of the R.A.F., aged 29, was admitted to a Military Hospital on February 23, 1944. He gave the following history: On September 21, 1943, he fell from his bicycle on to the point of his right shoulder. He was momentarily dazed, but picked himself up, when he found that his right arm was "useless." He put the arm inside his coat and was able to proceed home unaided. The next day he reported sick and was found to have a fracture of the head of his right radius. He was treated conservatively but did not improve. The arm was then put in plaster but without benefit. In fact he got worse and became aware that his arm was "all wasted." On examination there was generalized wasting of the right upper extremity with localized wasting and weakness of the flexors of the

wrist and fingers and all the intrinsic muscles of the hand. There was an overlay of variable (probably hysterical) weakness combined with a coarse tremor on attempted movement. The sensory impairment was consistent with an ulnar nerve lesion. There were no signs indicative of a cervical sympathetic lesion. The right triceps jerk was weaker than the left. A sweating test showed a generalized bilateral hypohydrosis of an unspecific type. The clinical diagnosis was thought to be a traction lesion of the right brachial plexus with an hysterical overlay. Needle electrodes were inserted into the right thenar and hypothenar muscle groups and fibrillation action potentials obtained in all positions of the needle point. Fibrillation action potentials were similarly obtained from the superficial forearm flexor muscles. Motor unit action potentials were also obtained on voluntary movement. In the supraspinatus and deltoid muscles on the other hand, vigorous fibrillation action potentials were obtained in one position of the needle point only, in a series of 12 needlings in each muscle. The areas fibrillating were very small but could be found again when the needle was re-inserted. In all other positions there was electrical "silence" at rest. On voluntary movement there were sufficient motor unit action potentials to obliterate completely the time-base tracing on the oscilloscope.

When a denervated voluntary muscle in Man has undergone morphological change resulting in fibrosis, no action potentials can be recorded either on movement of the needle point or at rest (Weddell *et al.*, 1943).

(3) *Factors Affecting Fibrillation of Denervation.*

The number and frequency of fibrillation action potentials vary from muscle to muscle and even from place to place in the same muscle. This variation is dependent in part on the position of the needle point in the muscle, for advancing the needle point through a fraction of a millimetre often suffices to vary the number of recorded spikes from 1 to as many as 4. As has been demonstrated in experimental animals, the radius from which the needle records is smaller in the case of a fibrillation action potential than a motor unit action potential; thus the directional properties of the electrode become more apparent, and fibrous tissue planes and even blood-vessels are probably effective in "insulating" the point of the electrode. For this reason it is advisable to shift the needle point to a number of different positions within the muscle in order to assess the "quantity" of fibrillation activity. It is, of course, possible that the needle point damages blood-vessels in some cases, giving rise to an extravasation of blood which surrounds and thus insulates the electrode. This is presumably unusual in view of our findings in experimental animals in which such an occurrence was very rare.

There are other factors affecting the number and frequency of the action potentials which can be recorded from denervated muscle, essentially the same as those pertaining in the case of experimental animals. They are

of particular importance in man, however, if action potential recording is to be employed as a diagnostic aid.

Temperature.—As in the case of experimental animals, local cooling of the part under examination decreases the number and frequency of the fibrillation action potentials and may even bring about their cessation. Conversely, warming the part increases the activity or may even reveal its presence in a muscle which otherwise appears inactive, as the following example shows.

Sgt. E. B., aged 36, of the R.A.F., was examined at a Military Hospital on July 29, 1943. He complained of increasing weakness of the hands during the past four years, and for the last four to five months he had noticed progressive wasting of the intrinsic muscles of both hands. There was a diminution of sensibility affecting all modalities over the distribution of C.8 and T.1 dermatomes on both sides and the sweating test showed a hypohydrosis over the same area. Electromyographic recordings were made from the muscles of C.8 and T.1 distributions on both sides. On insertion of the needle electrode there was an outburst of motor unit action potentials and on voluntary movement against resistance the motor unit activity was sufficient to obscure three-quarters of the base line on the oscilloscope. No electrical activity was recorded when the muscles were at rest, however. In addition to the sound of motor unit action potentials it was thought that fibrillation action potentials were also heard when the needle was inserted into the muscles, but it was difficult to be sure of this. The patient's hands, which were cold and blue at the time of the test were then put into hot water (44° C.) for fifteen minutes. After this, insertion of the needle electrode evoked a definite outburst of fibrillation action potentials as well as motor unit action potentials, and a vigorous residue of repetitive fibrillation action potentials were obtained. The hands were then put into cold water (10° C.) for fifteen minutes, and the electromyographic recordings repeated. No fibrillation action potentials were recorded and it was difficult to detect an outburst of fibrillation action potentials on insertion of the electrode. During the course of his stay in hospital the patient had massage and a course of radiant heat therapy for his wasted muscles; this improved both the colour and resting temperature of the skin. In subsequent electromyographic recordings fibrillation action potentials were recorded without preliminary warming of the patient's hands.

Thus in all cases of suspected lower motor neurone denervation when no fibrillation action potentials can be recorded, the part should be warmed either by radiant heat or immersion in hot water until the surface reaches a temperature not far short of that of the blood. If no fibrillation action potentials can then be obtained after shifting the needle point into a number of different positions in the muscle, it may be assumed that no denervated muscle tissue is present in the regions sampled.

To obtain further examples of the effect of local temperature on fibrillation action potentials, electromyographic recordings were made from four cases of complete ulnar nerve interruption, and two cases of brachial plexus lesion in which all the muscles below the elbow were paralysed.

The recordings were made one week after the patients had arrived in England from overseas where they had been wounded five months previously. In each case the affected muscles were grossly wasted, the joints very stiff, and the hand blue and cold as compared with the normal side. The patients stated that they had had no physiotherapy owing to operational conditions and had worn their splints continuously since the date of wounding.

An outburst of fibrillation action potentials and a few repetitive fibrillation action potential spikes which died away within two seconds were obtained from all the denervated muscles without preliminary warming. After two weeks of vigorous physiotherapy in the form of radiant heat, massage, galvanic stimulation and passive movements, the extremities were warmer and less stiff. Electromyographic recordings now showed, again without preliminary warming of the affected parts, vigorous outbursts of fibrillation action potentials on insertion of the needle, followed in all cases by a series of repetitive spikes which continued as long as the needle was in position. The cases were followed for three months and electromyographic investigations carried out at two-weekly intervals. The fibrillation action potentials remained numerous and of high frequency. The wasting appeared less in the case of the ulnar nerve lesions and was measurably less (a 2 cm. increase in circumference of the forearm) in one of the cases of the brachial plexus lesion, although denervation remained complete. These findings are interesting for two reasons. Firstly they confirm the observations of Solandt and Magladery (1940) that there is no direct relationship between muscle atrophy and fibrillation activity, and secondly, they suggest that the amount of fibrillation present is some indication of the efficacy of the treatment (physiotherapy) which the patient is having.

In another publication we have recorded experiments in which the warming and cooling of exposed denervated voluntary muscles in experimental animals were accompanied by the appearance and recession of visible fibrillations. Similar experiments were repeated in five cases in which denervated muscles were seen at operation. The muscles exposed were the supinator, extensor carpi radialis longus and neighbouring muscles, biceps and coraco-brachialis, flexor carpi ulnaris, triceps and the posterior belly of the digastric muscle. In all cases, when the affected muscles were warmed by radiant heat immediately after bathing with warm isotonic saline solution, isolated surface twitchings were seen by reflex illumination but they were not so widespread as those seen in animals under similar conditions. Withdrawal of the radiant heat caused the twitchings to disappear within a few seconds.

A rise of blood temperature, whether from sepsis or other causes, usually results in an increase in the fibrillation activity of denervated voluntary muscle. The following is an example:—

Pte. E. M., aged 21, while convalescing from the effects of a severe head injury sustained on May 7, 1943, accidentally fell 20 ft. through a skylight and received multiple injuries; more particularly, he had a compound perilunar dislocation of the left wrist with a partial lesion of the left ulnar nerve, and a compound fracture of the right femur. The site of the femoral fracture became infected. Electromyographic recordings were made from the ulnar intrinsic muscles of the left hand four weeks after the injury, when the patient was running a temperature of 103° F. as the result of his infection. They all showed a few motor unit action potentials on insertion of the needle and 1 to 2 repetitive motor unit action potentials on attempted movement. Vigorous fibrillation action potentials were also distinguished when the needle was inserted and were followed by a constant shower of high-frequency fibrillation action potential spikes. Electromyographic recordings were repeated three weeks later when the patient's temperature had fallen to normal. The number and frequency of the fibrillation action potentials was not so large on this occasion. The hand was warm and normally moist at the time of the second examination whereas at the first it was hot and dry.

This case, in conjunction with others in which action potentials were recorded before and after a rise of body temperature, shows that temperature, whether raised by the blood or artificially through the skin, is effective in increasing the number and frequency of fibrillation action potential spikes. In this connection, it is interesting that the time of onset as well as the quantity of fibrillation activity is greater in the sacrospinalis muscles than in the limb musculature in Man. This may be related to a greater average temperature or even a greater metabolic rate in the sacrospinalis muscles, for we have shown in experimental animals that fibrillation activity is related not only to temperature but also to metabolic rate.

Prostigmin.—Cannon and Haimovici (1939) have stated as a general law that the degeneration of neurons which normally deliver impulses to a structure are attended by a lowered threshold to submaximal chemical stimuli applied to it. Thus the phenomenon of fibrillation of denervation in striated muscle is associated with an increased sensitivity of the muscle to circulating acetylcholine (Frank, Nothmann and Hirsch-Kaufmann, 1922). Denny-Brown and Pennybacker have also shown that a drop of 1:1,000 acetylcholine placed on a denervated cat's muscle increases the amount of visible fibrillation. It has been claimed by Levine *et al.* (1942), working on rats, that prostigmin increases the amount of fibrillation in denervated muscles and they explain this finding by stating that the drug acts on the neuromuscular junction and prevents the destruction of acetylcholine and so "potentiates" its action. Our findings in rabbits and

Man confirm this observation. The work of Levine *et al.*, however, is open to criticism on the grounds that they used the method of observation in their analysis of an increase or decrease of fibrillation as the result of the administration of drugs. They do not mention that care was taken to keep the surface of the exposed muscle at constant temperature; failure to take such a precaution, as already shown, is liable to cause errors in interpretation. It is probable that their finding that atropin decreases fibrillation of denervation was due to this cause, for Solandt and Magladery, using needle electrodes through intact skin, came to the conclusion that atropine was without effect. The following is an example of the action of prostigmin in Man.

Pte. L. G., aged 18, on July 17, 1943, accidentally discharged his rifle, the muzzle of which was in his right axilla. At operation the next day the radial nerve was found to be divided, but the remaining nerves and vessels were intact and apparently uninjured. Debridement was carried out and a skin graft applied. After the wound had healed he was transferred to a Military Hospital for nerve suture. Electromyographic recordings were made from muscles of the forearm supplied by the radial nerve on October 4, 1943. Insertion of the needle gave rise to an outburst of fibrillation action potentials, and 1 to 2 repetitive fibrillation action potentials were obtained from the majority of positions of the needle in all the muscles supplied by the radial nerve (average from 10 needlings). 2·5 mg. of prostigmin and 1 mg. of atropin sulphate were then given subcutaneously. After twenty minutes, marked fasciculation was noted in all subcutaneous normal upper extremity muscles. The denervated muscles were not fasciculating, but they now showed a vigorous outburst of fibrillation action potentials on insertion of the needle, and a constant residue of 3 to 4 fibrillation action potentials (average from 10 needlings) (Plate IX, figs. 2 and 3).

Thus prostigmin increases fibrillation activity in Man and is also of value in eliciting fibrillation for diagnostic purposes as the following case illustrates.

Sgt. E. B., aged 36, of the R.A.F., was examined at a Military Hospital on July 29, 1943. He complained of increasing weakness of the hands for the last four years, and he had noticed progressive wasting of the intrinsic muscles for the last four to five months. On examination there was weakness and wasting of all the intrinsic muscles of both hands and impaired sensibility to all modalities over C.8 and T.1 dermatomes, and also hypohydrosis over a corresponding area. Needle electrodes were inserted into the hypothenar muscles on the right side. Motor unit action potentials were recorded both on insertion and on voluntary movement, but no fibrillation action potentials were definitely recorded. The hands were cold and blue at the time of this examination. He was given 2·5 mg. of prostigmin combined with 1 mg. of atropin, subcutaneously, and further recordings were made half an hour later. There were now fasciculations involving the superficial trunk and extremity muscles but the hands were still cold and blue. Fibrillation action potentials were now recorded in profusion from the muscles of the right hypothenar eminence. One half-hour later when fasciculations were no longer visible, fibrillation action potentials were still obtainable. Two hours later all fibrillation activity

had ceased in the right hypothenar muscles. On the next day the effects of warming and cooling the hands were investigated. Warmth evoked the fibrillation activity in the same way as prostigmin and cooling the hands abolished it.

(4) *Summary.*

(1) Fibrillation action potentials can be recorded from denervated voluntary muscles in Man providing the muscle under examination is warm (muscle and overlying skin at approximately blood temperature).

(2) Fibrillation action potentials are of two types, those evoked by the insertion of the needle, due to mechanical stimulation, and those which repeat rhythmically, due, presumably, to chemical stimulation.

(3) The time-course of fibrillation activity in Man is longer than in experimental animals. In limb musculature the onset is from the sixteenth to the eighteenth days, while in sacrospinalis muscles between ten and twelve days.

(4) Fibrillation action potentials take the form of rhythmic mono- or diphasic spikes 1 to 2 milliseconds in duration and up to 100 microvolts in amplitude repeating at variable rates from 2 to 10 per second.

(5) Muscle denervated for many years may give rise to fibrillation action potentials. We have obtained fibrillation action potentials from muscles denervated for eighteen years; nevertheless the number and frequency of the action potentials are less than in recently denervated muscles.

(6) Fibrillation action potentials can be obtained from partially denervated muscles. In cases where the number of motor units separated from their nerve supplies is minimal the electrode will have to be moved freely through the muscle before fibrillation action potentials are recorded. Spontaneous repetitive motor unit action potentials uninfluenced by voluntary effort, as well as fibrillation action potentials, are often obtained from muscles in cases of slowly progressive peripheral nerve interruption.

(7) In certain cases where the lesion is presumed to be the result of axonal interruption, fibrillation action potentials cannot be recorded. Such findings are explained on the assumption that (*a*) the disease process may involve the muscle fibres; (*b*) the denervated muscle fibres may have undergone morphological changes; (*c*) the nerves to the muscles in question may not have undergone axonal interruption but be in a condition of reversible ischæmic block.

(8) The number and frequency of the fibrillation action potentials recorded from denervated voluntary muscle in Man may be increased by raising the temperature of the circulating blood or warming the muscle under examination. On the contrary, a low temperature decreases the activity.

(9) The number and frequency of the fibrillation action potentials recorded from denervated voluntary muscle in Man increases following the administration of prostigmin.

(10) There is no apparent relationship between the number and frequency of fibrillation action potentials and muscle atrophy.

(11) Denervated muscles which have received adequate physiotherapy as judged by clinical examination fibrillate vigorously, whereas denervated muscles which have been long splinted and which have not been treated fibrillate feebly and, indeed on occasions no repetitive fibrillation action potentials can be recorded.

VI.—The Action Potentials from Muscles in the Case of Reversible Ischæmic Nerve Block.

(1) *Introduction and Definition.*

Denny-Brown and Brenner (1944*a*) have demonstrated in cats that ischæmia of the sciatic nerve trunk (resulting from pressure) blocks motor conduction only, for a period of two to eighteen days. Histologically, the nerve remains intact below the level of the compression, or only occasionally shows beading of myelin sheath or axis cylinder. At the site of compression the histological picture is grossly abnormal and resembles segmental periaxial neuritis but is not so extreme. In this condition there is no loss of excitability of the nerve below the level of the lesion, and muscle atrophy is not so marked as that following nerve section. The paralysed muscles do not fibrillate. Recovery of conduction is rapid and complete, but restoration of the histological picture to normal requires more than two months and the authors suggest that it may never be complete. Denny-Brown and Brenner (1944*b*) have clearly shown that pressure alone does not abolish nerve conduction but that it is the ischæmia resulting from pressure which is the responsible factor.

Parallel clinical conditions due to reversible ischæmic nerve block are afforded by "Saturday Night Paralysis," "Crutch Palsy," and "Bell's Palsy." These cases cannot be distinguished from paralysis due to axonal interruption by clinical examination alone within a short time of the onset of the paralysis. The faradic response, however, remains brisk and the nerve below the level of the lesion remains normally excitable. Thus the electrical reactions in these cases are a useful diagnostic guide (as pointed out by Erb, 1876) although under certain circumstances a brisk galvanic and faradic response of individual muscles may still be obtained where a large number of axons have been interrupted. The following case illustrates this point.

(2) *Observations.*

"*Saturday night paralysis.*"—Pte. T. D., aged 19, sustained a left radial nerve palsy of unknown ætiology on February 3, 1944. There was a sudden onset of weakness of finger, wrist and thumb extension. Within twenty-four hours paralysis was complete and there was sensory impairment within the territory of the posterior cutaneous nerve of the forearm and superficial radial nerve. The condition was suspected to be of the nature of a severe "Saturday Night Paralysis." He was given electrical treatment but failed to improve. On examination at a Military Hospital on May 1, 1944, the radial nerve felt normal in the region of the radial groove of the humerus. Passive movements were full at all joints in the upper extremity. There was no wasting of the arm, but 1½ cm. wasting of the left forearm. While full voluntary power was retained by the triceps all muscles of radial supply below this were completely paralysed. All the paralysed muscles responded briskly to faradism and galvanism, but stimulation of the radial nerve in the humeral groove was not followed by contraction of the muscles below this level. The diagnosis was considered to be a pressure palsy and rapid and complete recovery expected. Electromyographic recordings from the paralysed muscles showed a vigorous outburst of fibrillation action potentials on insertion of the electrode followed by many repetitive fibrillation action potential spikes of high frequency. Insertion of the needle also elicited an occasional motor unit action potential, while in the brachio-radialis there was a single motor unit action potential which repeated rhythmically for an indefinite period but was not affected by voluntary effort. No motor unit action potentials were recorded in response to attempts at voluntary movement. These findings indicated that the nerve had been severely damaged; most of the axons having been divided but a few showing the condition of reversible ischæmic block. The subsequent clinical course of the case confirmed this diagnosis. Four weeks after the first electromyographic examination, a further series of needlings was done. Fibrillation action potentials were still obtained from the brachio-radialis muscle and a few motor unit action potentials on insertion of the electrode. On attempted voluntary movement, however, there were short high-frequency outbursts of motor unit action potentials of small amplitude, some of which were highly polyphasic; a condition typical of regeneration (*vide infra*). On clinical examination an occasional flicker was observed in brachio-radialis on attempted movement.

In this case the inexcitability of the nerve below the level of the lesion with a current of normal threshold was a guide to its condition. The exact diagnosis, however, was established by electromyographic recordings. It seems not improbable that the retention of the faradic response and the brisk galvanic response were related to the presence of the few undegenerated nerve fibres.

Electromyographic recordings have been made from a number of muscles where reversible ischæmic block was suspected in view of the clinical course of the case, and our findings indicate that it is of some value in diagnosis and prognosis in such conditions. The following are examples:—

"*Crutch palsy.*"—Sgt. A. G., aged 42, was recovering from the effects of an infected compound fracture of the right tibia and fibula, sustained on March 1, 1941, and started to walk, using crutches, on September 16, 1941. On December 9, 1941, he

first noted slight weakness of his right hand. The next day there was a complete wrist drop on the right side and he was unable to abduct his thumb. Two days later he noted slight weakness of a similar nature on the left side. On examination at this time he had complete paralysis of the muscles supplied by the right radial nerve, including the outer head of the triceps muscle. There was also weakness of the muscles supplied by the radial nerve on the left side. On January 3, 1942, there was slight functional recovery of the right extensor communis digitorum and extensor carpi ulnaris muscles; the remaining muscles supplied by the right radial nerve, however, were still inactive. Electromyographic recordings were made from the paralysed muscles. The right brachio-radialis, extensor carpi radialis longus and brevis muscles all showed an outburst of motor unit action potentials on insertion of the needle electrode. In the brachio-radialis muscle at rest there was a single motor unit action potential which repeated rhythmically but was not under voluntary control. One fibrillation action potential was also recorded. No action potentials were recorded from the remaining paralysed muscles at rest. On attempted movement a few motor unit action potentials under voluntary control were recorded from all the paralysed muscles. The affected muscles on the left side were also examined. There was an outburst of motor unit action potentials on insertion of the needle electrode and on maximum voluntary effort there was sustained motor unit activity sufficient to obliterate practically the whole of the time-base tracing of the oscilloscope screen. No fibrillation action potentials were recorded. On January 22, 1942, voluntary movement could be demonstrated in all muscles supplied by the radial nerve. On March 6, 1942, all muscles were acting powerfully, but full functional recovery did not take place until April, 1942. The electromyographic findings in this case indicated a block of conduction with minimal denervation. The clinical course of the case substantiated these observations.

"Bell's palsy."—A further example of electromyographic findings in reversible ischæmic block is afforded by observations made in a case of "Bell's Palsy."

B. J., a medical student, woke up on the morning of November 25, 1942, with a complete right facial nerve paralysis. He could remember no obvious predisposing cause or prodromal symptoms, but for a few hours after waking with the paralysis he was aware of an increased auditory acuity on the affected side. He was at first seen for electromyographic recordings on December 27, 1943, at which time decompression of the facial nerve was contemplated, for the paralysis remained clinically complete, and although the faradic response was still present it was difficult to obtain satisfactory results which could be compared with the opposite normal side owing to the pain engendered by the stimulus. The threshold was thought to be increasing. Needle electrodes were inserted into the cheek muscles, the orbicularis oris and frontalis muscles. The insertion of the electrode provoked an outburst of motor unit action potentials only. No fibrillation action potentials were encountered in any position of the needle point. On attempted movement, a few motor unit action potentials were obtained in some positions of the needle point, but the activity could only be sustained for two or three seconds. The picture was one of reversible ischæmic block without axonal interruption. It was decided to delay operation on account of these findings and electromyographic recordings were made twice weekly for the next two weeks. On each occasion a generally similar picture was obtained, except that progressively more motor units under voluntary control were encountered. On the occasion of the last examination, voluntary movements were returning and motor unit activity was vigorous, but there were

still no fibrillation action potentials. Within two weeks of our last examination, complete recovery had taken place and it was not possible to determine clinically which side had been affected. The complete absence of fibrillation action potentials and the length of the paralysis in this case are particularly interesting.

Following laminectomy.—Reversible ischæmic nerve block has been observed in the sacrospinalis muscles following laminectomy for prolapsed intervertebral disc and other conditions. We have supposed that the block in these cases was due to the pressure of the self-retaining retractors, leading to ischæmia of the intramuscular nerve fibres. In the 25 cases of laminectomy already quoted, in which the muscles were detached from the vertebræ on both sides, electromyographic recordings were made from the sacrospinalis muscles at intervals ranging from nine days to twelve months following operation. As already stated, action potentials indicative of muscle denervation have been observed as early as ten days after operation in these muscles. Fourteen days after operation fibrillation action potentials were most numerous about 1 cm. lateral to the incision, and in this position there was no motor unit activity whatever. 2 to 3 cm. lateral to the incision there were fibrillation action potentials but, in addition, an outburst of motor unit action potentials appeared on insertion of the needle electrode. There were no sustained motor unit action potentials in response to spinal movements. Further laterally still, no fibrillation action potentials were recorded but there was a vigorous outburst of motor unit action potentials on insertion of the electrode; very few repetitive motor unit action potentials were recorded on active movement of the spine, however. The areas examined lateral to the incision were tender to palpation, and insertion of the needle caused more discomfort than usual; for this reason it was thought possible that the absence of motor unit action potentials might be due to a protective reflex inhibition rather than reversible ischæmic block. This was negatived to some extent by needling the muscles 2 cm. above and below the extent of the scar and finding full motor unit activity on active spinal movement, a procedure which clearly involved the affected skin and muscles. Moreover, in another series of 25 cases where the muscles had been separated from the spines and laminæ on one side only, motor unit activity was normal in all positions of the needle point on the undisturbed side, although the insertion of the electrode caused equal discomfort on both sides. Finally, in one case of laminectomy for prolapsed intervertebral disc undertaken recently, hand retractors only were used and the muscles submitted to minimal trauma during the operation. Twelve days after operation there was no evidence of ischæmic block 2 cm. or more from the mid-line scar, full motor unit activity being displayed.

In the first series of cases referred to above in which the sacrospinalis muscles were detached from both sides of the vertebræ, electromyographic recordings made three weeks after operation showed the return of a number of sustained motor unit action potentials 2 to 3 cm. from the scar and full motor unit activity more laterally. Three months after operation the motor unit activity had returned to normal to within approximately 1 cm. of the mid-line scar, although more medially only fibrillation action potentials were recorded. In two cases which were examined one year after operation, there was still vigorous fibrillation activity and absence of motor unit action potentials close to the scar.

These findings demonstrate that the operative procedure adopted leads to a thin band of completely denervated muscle close to the incision, while more laterally, although there is a certain amount of denervation, the absence of repetitive motor unit action potentials over such a wide area a short time after operation is due to a reversible ischæmic block.

Following these observations we found that if precautions were taken to minimize the pressure on the sacrospinalis muscles from retractors, full motor unit activity was rapidly restored following operation except for a narrow band of denervation close to the mid-line. In our cases of lumbar laminectomy, denervation of the sacrospinalis was not a prominent feature. Reversible ischæmic block was more in evidence and the recovery of function was rapid and complete in all cases. We have examined a single case of cervical laminectomy from the electromyographic point of view; and in this case denervation was the prominent feature and the recovery of the patient was not effected until nerve regeneration had taken place.

A.C.1 J. G., of the R.A.F., aged 37, was admitted to a Military Hospital on August 15, 1942, complaining of a thirteen months' history of increasing weakness of the legs and arms and incontinence of urine. He gave no history of trauma. On examination the patient had a severe spastic quadriplegia with a correspondingly severe sensory impairment below the C.5 segment. In addition, he had wasting and weakness of the left deltoid, biceps, and spinati muscles with the electrical reactions of R.D. in the anterior and middle fibres of the deltoid. X-rays showed a narrowing of the intervertebral space between C.5 and 6. At operation on September 3, 1942, a cervical laminectomy was performed and the deep cervical muscles dissected off the spines and laminæ from C.3 to C.6 inclusive and self-retaining retractors put into position. The spines and laminæ were then removed. A prolapsed intervertebral disc was encountered between the 5th and 6th cervical vertebræ on the left side in the lower angle between the lateral surface of the dura and the 6th cervical nerve root, which was stretched over it. The protrusion was removed and the wound closed in layers. Following operation, the patient made a remarkable recovery. The symptoms and signs referable to interruption of pathways in the central nervous system receded. One month following his operation (during which time he had been given physiotherapy) he was allowed to

get up from his bed without neck support and within a further month he had started walking. He continued to improve and to take more and more exercise until December 15, 1942, when he had an exacerbation of symptoms and signs referable to compression of the spinal cord at the C.5 level. He was at once put to bed and the symptoms and signs abated. On December 29, 1942, needle electrodes were inserted into the deep posterior cervical muscles on either side of the mid-line scar. They were found to be completely denervated. His neck was then put in a plaster collar and the cervical spine immobilized in extension, and he was once again allowed up without untoward results. On February 8, 1943, the plaster collar had become loose and cracked and he once more developed symptoms and signs of cord compression. Electromyograms on February 14, 1943, still showed complete denervation of the deep, posterior cervical spinal muscles with no motor unit activity on insertion of the needle electrode, and spinal fusion was recommended. The patient, however, refused to consider further operation and requested that he might be given another plaster collar. This was done, and he once more improved. On March 23, 1943, the collar was removed and electromyograms of the neck muscles now showed motor unit activity in the previously denervated cervical spinal muscles. He was given vigorous physiotherapy and allowed out of bed for increasing periods. There was no recurrence of symptoms or signs up to the time of his discharge four months later. At this time motor unit activity was vigorous in the spinal muscles and also in the left deltoid. The latter now responded to faradism in all its parts, had increased in bulk and was contracting voluntarily. In this case the condition of denervation of the spinal musculature following laminectomy was distinguished from reversible ischæmic block by means of electromyography. The case also illustrates that a greater amount of spinal muscle denervation occurs following a cervical laminectomy as compared with a similar operation in the lumbar region, a fact recognized clinically (Cairns, 1943).

(3) *Summary.*

(1) In cases of reversible ischæmic block, motor unit action potentials can always be obtained on insertion of the needle electrode and it is usual to find a few repetitive motor unit action potentials which may or may not be under voluntary control.

(2) Fibrillation action potentials are absent or few in number and may be confined to discrete positions in the affected muscles.

VII.—The Action Potentials from Re-innervated Muscles.

(1) *Introduction.*

We have been unable to find any detailed description of the action potentials from re-innervated muscle in Man, but Berry *et al.* (1944) have recently correlated the electrical activity of regenerated nerve fibres with their histological appearance in the cat, and have shown that stimulation of the regenerated nerve fibres causes muscle contractions as early as 23 days after the suture, whereas the animal does not use the muscle for 50 to 60 days after operation although considerable regeneration has taken place by that time.

(2) *Observations.*

We have obtained records of the action potentials in muscles from the time of denervation through to complete functional recovery.

Experimental case.—In our experimental case in Man (R.E.P.) the nerves to the left brachio-radialis and extensor carpi radialis longus muscles were crushed 5 cm. from their entrance into the muscles. As already stated, eighteen days following denervation a continuously repetitive series of action potentials indicative of fibrillation was obtained. This electrical activity continued unabated until the fortieth day after nerve interruption, when our records show a steady decline in the number of action potential spikes recorded during the successive series of needlings. It is impossible, however, to make a quantitative statement on this point, for the conditions under which the records were made were not strictly uniform. On the fifty-fifth day after nerve interruption, in addition to fibrillation action potentials, three motor unit action potentials of low amplitude (one of which was polyphasic) were obtained, in response to attempts at voluntary contraction, in the region of the entrance of the nerve into the brachio-radialis muscle (position tatooed into the skin at the time of operation). The action potentials repeated at a rate of about 20/second, but one of them could only be sustained for two to three seconds after which it was not recorded again until a rest interval of ten minutes had elapsed. At this time, although no contraction could be palpated, the subject stated that he could "feel" the muscle contract. Now, the muscle was adherent to the skin, and, although careful observation showed no movement during the outburst of motor unit action potentials, it was not improbable that the subjective sensation was due to this, for a flicker of movement was easily visible two days later when a larger number of motor unit action potentials, whose activity, however, could still not be sustained, were recorded. It is interesting that, although the number of motor unit action potentials rapidly increased, all could not be maintained as a continuous stream of impulses (many only lasting for one to two seconds) until ten days following the first appearance of motor unit action potentials. The subject stated that he was aware that contraction on attempted movement could not be maintained at a steady level during this time, however hard he tried. These findings seem to us to be directly related to those of Berry *et al.* in relation to delay in neuromuscular transmission following regeneration.

Within a week following the appearance of the first motor unit action potentials in the brachio-radialis muscle, they could be obtained in varying numbers throughout the muscle; few were obtained in the lower and upper thirds, the greatest number still evolving close to the entry point of the nerve. Two weeks later, motor unit action potentials could be obtained evenly distributed throughout the muscle. Fibrillation action potentials could also be obtained in all positions of the needle point throughout the muscle up to this time, although in greatly reduced numbers; indeed, twelve months after operation an occasional fibrillation action potential was recorded in certain positions in the muscle when no detectable weakness could be recorded clinically.

Motor unit action potentials were first obtained from the extensor carpi radialis longus muscle fifty-nine days following denervation; they were similar in appearance to those in the brachio-radialis muscle and also difficult to sustain at first. Fibrillation activity similarly declined in this muscle from the fortieth day onwards. Despite the appearance of motor unit action potentials, clinical signs of recovery did not appear for nine days following the recording of the first motor unit action potential. Twelve days following the appearance of the first motor unit

action potential, contraction was judged to be grade 2 (Medical Research Council (1942) classification = just sufficient to move a joint). Recovery in function was rapid in both muscles and, within two months of the onset of functional recovery had reached grade 4 (= moderate power). It was still possible to obtain fibrillation action potentials throughout the muscle at this time however.

Interval between appearance of motor unit action potentials and functional recovery.—Recovery of function in this case was rapid and ultimately complete, full power and control of movements having returned by twelve months from the date of operation. The early stages of recovery were particularly rapid and there was only a short interval between the appearance of the first motor unit action potentials and signs of recovery on clinical examination. The length of this interval varies greatly and is dependent on a number of factors, among which are the "quality" of re-innervation, and the anatomical position and action of the re-innervated muscles, for in some muscles it is much more difficult than in others to detect small degrees of movement clinically. The following case illustrates these points.

Pte. M. G., aged 24, on December 23, 1942, was struck on the left wrist by the starting handle of a lorry which back-fired. The wrist was lacerated and the ulnar nerve damaged. The wound was excised on the day of the accident and, after this, sensation slowly improved over the ulnar one and a half digits but there was no significant recovery of movement in the intrinsic muscles of the hand. On July 22, 1943, there was paralysis of the ulnar intrinsic muscle of the left hand, including the flexor pollicis brevis. All passive movements were full. There was no abnormality of sweating over the ulnar area and sensory loss over the distribution of the palmar cutaneous branch was minimal. On February 24, 1943, the left ulnar nerve was explored at the wrist and a hard neuroma, involving the motor division of the nerve only, was encountered. It was resected and the nerve sutured after a transplant at the elbow had been effected. Electromyographic recordings on April 26, 1943, showed fibrillation action potentials from all muscles supplied by the left ulnar nerve distal to the wrist and paralysis was complete. However, two motor unit action potentials were recorded from the proximal third of abductor digiti minimi on attempted movement, but these were only observed after a subcutaneous injection of 1 mg. of prostigmin. Electromyographic examinations were repeated on May 7, 1943, and again fibrillation action potentials were recorded from all the intrinsic muscles of the hand, but it was now possible to record motor unit action potentials from all parts of the abductor digiti minimi muscle. There was still no functional recovery, however. On June 17, 1943, fibrillation action potentials were still present in all the intrinsic muscles of the left hand in diminished numbers, but there were now one or two motor unit action potentials in all except the first dorsal interosseus muscle in which, however, the number of fibrillation action potentials recorded had greatly diminished. On June 24, 1943, motor unit action potentials were obtained from all the intrinsic muscles of the left hand, but again no movement could be detected clinically. On September 16, 1943, there was a large increase of motor unit activity throughout the ulnar intrinsic muscles, and feeble movements of the hypothenar muscles and probably some movement of the 1st dorsal interosseus muscle were observed. Movements referable

to the remaining interossei were indefinite. Passive movements at all joints were full at this time.

The delay between re-innervation and some of the detectable movements in this case (three to four months) may involve another factor in addition to those already mentioned. Re-innervated interossei (following nerve suture particularly) are not capable of independent movements, at least in the early stages. This is consequent on collateralization and the change in destination of many axons in the course of re-innervation. Electromyographic recordings illustrate these "mass" or "associated" movements well; for instance, with electrodes recording simultaneously from abductor minimi digiti and the first dorsal interosseus muscle, an attempt to adduct the thumb or abduct the little finger as separate isolated movements is followed by an outburst of action potentials from both muscles whichever movement is attempted. Thus a number of the muscles will be opposing the actions of their neighbours and further increase the difficulty of detecting feeble joint movements.

Form of the action potentials.—The forms of the motor unit action potentials during the course of re-innervation are of some interest and value in diagnosis and prognosis. The action potentials of individual motor units vary in amplitude and duration more than in normal muscle. In the early stages of re-innervation particularly, the transient showers of motor unit action potentials on insertion of the needle electrode may resemble large fibrillation action potentials except for their frequency, which is usually not lower than 20/second. In the early stages of re-innervation of the facial musculature (where motor unit action potentials are normally smaller and of shorter duration than in limb muscles), motor unit action potentials may on occasion be very difficult to distinguish from fibrillation action potentials except in relation to voluntary movement (Plate IX, fig. 4). The difficulty is not great if examinations have been made at different stages in the course of the degeneration-regeneration cycle however. In addition, such action potentials are usually associated with complex highly polyphasic spikes of medium or low amplitude (100-500 microvolts) in other positions in the muscle, and errors of interpretation are not likely to occur when experience has been gained. We have explained the phenomenon of low amplitude and short duration of the action potentials of motor units in the early stages on the assumption that, as the result of partial re-innervation, individual motor units do not consist of as many muscle fibres as normal, and this is confirmed by the number of fibrillation action potentials which can still be recorded. In addition, all the muscle fibres within the unit may not contract in response

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to a nerve impulse in the early stages of re-innervation. This is a possible corollary of the impossibility of sustaining motor unit action potentials when they first appear. It is specifically illustrated in the following case.

Pte. K. T., aged 24, was wounded in the left arm by a bullet on October 4, 1943. He was examined at a Military Hospital on January 22, 1944, and found to have a recovering radial nerve palsy, for in the brachio-radialis muscle voluntary movements were moderately powerful, and fibrillation action potentials could still be obtained from all parts of the muscle into which the needle was inserted, in addition to motor unit action potentials, of which a number were highly polyphasic. One such polyphasic unit was observed in which a single spike within the complex was only apparent at every fourth repetition of the action potential. Recording was continued for some three minutes during which the phenomenon persisted. Throughout this time there was no other change in the form of the action potential.

Mention has already been made of the common appearance of polyphasic action potentials in regenerating muscles. When they occur they are very valuable from the diagnostic point of view. They are smaller and more numerous than polyphasic action potentials seen when recording from normal muscles (in which they are commonly among the largest action potentials seen) and usually have more spikes within the complex. Complexes with as many as 12 spikes have been seen (Plate IX, fig. 5). The sounds to which they give rise are quite characteristic, being rough and deep-pitched. They can easily be distinguished from a synchronous discharge of motor unit action potentials by the absence of phasic changes during a prolonged contraction and by the change in frequency of the complex with increase or decrease of muscular tension. It is also possible to sample the action potentials from specific polyphasic motor units on successive days and to recognize them by their characteristic forms. In an earlier publication (Weddell *et al.*, 1943) we referred to these action potentials as "nascent" motor unit action potentials, an inaccurate term, as we now know, for while it is true that such polyphasic action potentials are most common during the early stages of re-innervation, some may persist for long periods, or none may be apparent even though re-innervation is known to have occurred. In addition, we believe it to be theoretically possible that closely similar action potentials may occur during the course of demyelinating diseases.

We have evidence that motor units are composed of widely separated muscle fibres in many re-innervated muscles and we have used polyphasic action potentials to demonstrate this, for such action potentials are easily recognized by their characteristic pattern. To give an example:—

Spr. G. J., aged 27, on March 18, 1943, sustained a compound fracture of the left elbow. When seen at a Military Hospital on October 14, 1943, he had a recovering left ulnar nerve paralysis. Electromyographic recordings from the

muscles supplied by the left ulnar nerve showed that there was motor unit activity in the flexor carpi ulnaris and the ulnar element of the flexor digitorum profundus muscle. Only a few fibrillation action potentials were recorded, and not in every position of the needle point in the muscle. A number of the motor unit action potentials were of medium amplitude and highly polyphasic. Motor unit action potentials and a considerable number of fibrillation action potentials were also recorded from all positions of the electrode in the ulnar intrinsic muscles of the left hand, but the motor unit activity was sufficiently vigorous to disturb the whole of the time-base tracing on the oscilloscope. Here also the majority of the motor unit action potentials were polyphasic, some exhibiting as many as 12 spikes within the complex. A polyphasic action potential was selected from flexor carpi ulnaris and its maximum amplitude recorded by shifting the electrode. The needle was then pushed through the muscle at right angles to the course of the muscle fibres and the action potentials observed for any changes in shape or amplitude. It was easy to recognize the action potential throughout this manœuvre, not only on account of its shape on the screen, but also by the specific character of the sound from the loud speaker. As the needle was pushed through the muscle there was very little change in the total amplitude of the action potential although the complete thickness of the muscle was traversed.

A similar experiment was carried out on our experimental case of nerve crushing in Man (R.E.P.) eighteen months after operation, when full functional recovery had taken place. There were a few polyphasic action potentials in the brachio-radialis muscle, each of which could be recognized by its characteristic sound. One of the spikes was selected, and at first recorded from the surface of the muscle; the needle was then slowly pushed right through the muscle at right angles to the course of the muscle fibres. Again there was no appreciable change in the amplitude of the action potentials during this manœuvre, but the shape changed slightly, in that some of the spikes composing the complex varied in amplitude to a small extent. We believe that these observations indicate that, following regeneration, the pattern of innervation within a muscle is abnormal, and more particularly that motor units are no longer discrete or composed of contiguous muscle fibres, but are scattered at random through the muscle. In the case of polyphasic motor unit action potentials from normal muscle, moving the needle electrode a short distance varies the amplitude of all spikes within the complex, and a movement of ½ cm. causes the amplitude to decrease almost to zero.

Our histological observations have demonstrated that following regeneration there is often a great variation in the diameter of the pre-terminal axons of the motor nerve fibres and also of the axonal elements of the motor end plates. The polyphasic character of many motor unit action potentials in the course of re-innervation we have explained on the basis of variation in conduction rate in the pre-terminal fibres of such motor units or variations in the latent period at the myoneural junctions. It is

possible that some of the polyphasic action potentials recorded from normal muscle (particularly when small) are explicable on this basis also, for, as shown by Weddell and Glees (1941), both degenerating and regenerating nerve fibres can be found in normal nerve trunks and in the fibres of the cutaneous plexus, probably the result of minor traumata which affect the normal individual from day to day. Minor local damage to intramuscular nerve fibres leading to a similar histological picture is thus likely to be not infrequent. It seems improbable on theoretical grounds that scatter of nerve fibres alone would account for polyphasic action potentials as suggested by Denslow and Hassett (1943).

Clinical applications.—It will be clear from the account given above that it is not always possible to determine from electromyographic recordings whether, or not, re-innervation has taken place. On occasions the quality of re-innervation may be good and the nerve fibres may grow back along their original pathways without distortion. Even in such cases, however, it is usual to find polyphasic action potentials in the earliest stages of re-innervation. In all cases when the continuity of the axon has been disturbed, the position is not so difficult. The following case illustrates these points.

Sgt. W. A., aged 27, as the result of a motor cycle accident on March 27, 1944, sustained a severe head injury with left cerebrospinal otorrhœa and a scalp laceration. His right shoulder and foot were bruised, and X-rays revealed a slight diastasis of the lower end of the left lambdoid suture and fractures of the 2nd, 3rd, 4th and 5th metatarsals on the right side. His retrograde amnesia was one and a half hours and his post-traumatic amnesia forty-eight hours. Nine days after the accident he first noticed that he was unable to abduct his right shoulder, but he was not sure if it had been quite normal before that. The paralysis was complete at first but had slowly improved since then. On examination on May 1, 1944, there were full painless passive movements at the right shoulder. The deltoid, supra- and infra-spinatus, and rhomboid muscles were all working but very weak, and wasting was minimal, although the deltoid was reported to be very "flabby." The remaining shoulder girdle muscles, arm, and forearm muscles were normal. The reflexes were normal and there was no sensory loss. The weakness was considered by some to be a partial C.5 root lesion, possibly a "serum neuritis" (A.T.S. serum given on March 27, the day of the accident) and by others to be due in great part to hysterical weakness following local trauma to the shoulder with a minimal weakness of C.5 distribution. Electromyographic recordings were made from all the main muscle groups of the right upper extremity on May 4, 1944. A number of fibrillation action potentials in all positions of the needle point were recorded from the affected muscles only, in addition to motor unit action potentials. Further recordings were made on June 1, 1944. On this occasion only an occasional fibrillation action potential was recorded from the affected muscles. Motor unit activity was vigorous in response to voluntary movement but a number of the action potentials were highly polyphasic and could not be sustained for more than a few seconds. Functional recovery had proceeded well but it was still considered by some to be poor in relation to the clinical state of the muscles. However electro-

myographically neuro-muscular transmission was not yet normal and it is not improbable that this accounted in great measure for the patient's residual weakness. On June 15, 1944, further recordings were made. On this occasion all the motor unit action potentials could be sustained indefinitely and far fewer polyphasic action potentials were seen. Functional recovery was said to have improved "out of all measure."

Points in regard to the value of electromyography in diagnosis and prognosis are afforded by the following case.

F/Lt. L., aged 40, was admitted to a Military Hospital on February 14, 1944, complaining of weakness of both shoulders. He gave the following history. On January 29, 1944, following a day of severe exertion (which included lifting a wounded man out of a plane) and two nights in which he slept in draughts, he suddenly had severe pain in the region of both deltoid muscles, made worse by movement and not fully relieved by large doses of morphia. He had a low grade pyrexia for two days following the onset of the pain, which continued to be severe for several days. On February 3, 1944, his right deltoid muscle was found to be completely paralysed and inactive to faradism. On examination at a Military Hospital on February 14, 1944, there was wasting and weakness of both left deltoid and left spinati muscles and complete paralysis of the right deltoid muscle without apparent involvement of the spinati. There was also some weakness of flexion and extension of the fingers on the left side. There were areas of sensory impairment over the region of both deltoid muscles with ill-defined margins. Electromyographic recordings were made from the affected muscles on February 24, 1944. The right supra- and infra-spinatus muscles gave rise to no fibrillation action potentials in any position of the needle point in a large series of needlings, and motor unit activity was full. He could abduct his arm to 75 degrees and external rotation was a powerful movement. The right deltoid muscle gave rise to numerous fibrillation action potentials in all parts. No motor unit action potentials were seen except in the anterior portion of the muscle where an occasional motor unit action potential was heard on insertion of the needle electrode. In two positions repetitive motor unit action potentials were encountered but they were uninfluenced by attempts at voluntary movement. On the left side fibrillation action potentials were obtained from the deltoid muscle in all its parts, but the number was less than on the opposite side and, in addition, motor unit activity was vigorous and sufficient to obliterate the whole of the time base tracing on the oscilloscope. Abduction of the arm on this side was also possible to 75 degrees but the left supraspinatus was virtually inactive. Fibrillation action potentials were obtained in profusion from all parts of the muscle, but only an occasional motor unit action potential could be recorded on insertion of the needle electrode and two spontaneous repetitive motor unit action potentials only (both uninfluenced by attempts at voluntary movement) were encountered. The left infra-spinatus showed a generally similar picture, except that a few motor unit action potentials under voluntary control were recorded. In the left extensor communis digitorum muscle there were occasional fibrillation action potentials with vigorous motor unit activity. The diagnosis given was "radiculitis," although the pattern of denervation electromyographically was not of root distribution. The prognosis was considered to be poor in view of the degree of denervation of the right deltoid. However, the fact that the spinati muscles on the right side had been spared suggested that the position of the lesion was fairly peripheral, involving the circumflex nerve rather than the C.5 root, and that regeneration should appear rapidly if the muscle was

fibrillation action potentials declined a short period before the first motor unit action potentials were recorded. Comparable observations have now been obtained from a large number of cases in the course of regeneration and we have supposed that it represents the re-innervation of muscle fibres before neuromuscular transmission is re-established (Berry *et al.*, 1944). Unfortunately the phenomenon is somewhat unreliable in its clinical application, for the factors affecting the number of fibrillation action potentials recorded with concentric needle electrodes are too numerous to be controlled without somewhat elaborate precautions and, in any case, an excessive number of needlings would be necessary before unequivocal results could be obtained. Arising out of these observations, however, we have used prostigmin in an attempt to re-establish neuromuscular transmission at an earlier stage of re-innervation in a number of subjects. The following case, which is typical of those we have chosen for this purpose, suggests that the method is of value.

L.A.C.W. J. A. B., aged 22, on October 1, 1942, started to have earache on the left side and some pain in the mastoid region. On the following day she woke with a left facial palsy, and two days after this pus began to discharge from the left ear. Conservative treatment was adopted and the discharge ceased within a week, but the facial paralysis remained complete. She was first seen for electromyographic investigations at a Military Hospital on February 21, 1943. On examination the facial paralysis was still clinically complete and there was no response of the paralysed muscle to faradic stimulation. Response to galvanic stimulation was brisk. Electromyographic recordings from the left cheek, orbicularis oris, and neighbouring muscles showed a large number of fibrillation action potentials. In addition, two small highly polyphasic motor unit action potentials under voluntary control were recorded from the corner of the mouth. They were successively repeated each time the patient tried to wrinkle her forehead. Recordings from the frontalis muscle showed many fibrillation action potentials but no motor unit activity. In view of the findings an expectant policy was adopted and physiotherapy, including exercises in front of a mirror, were advised. On May 7, 1943, a further electromyographic examination was made. Functional recovery had commenced and on attempting to wrinkle the forehead the angle of the mouth was elevated. Highly polyphasic motor unit action potentials, in addition to a few fibrillation action potentials, were obtained in all positions of the needle point in the cheek, orbicularis oris, and neighbouring muscles. No motor unit action potentials were yet observed in the frontalis muscle, however, although a number of fibrillation action potentials could still be obtained. The girl was now given 2½ mg. of prostigmin combined with 1 mg. of atropin subcutaneously. Immediately after this the electrode was inserted into the paralysed frontalis muscle where it was maintained in a chosen position from which a number of fibrillation action potentials were recorded. The patient was then asked to wrinkle her forehead and show her teeth at three-minute intervals. After eighteen minutes two small diphasic motor unit action potentials were recorded in response to these movements. They could not be sustained for more than a few seconds at a time, however, and nine minutes later were no longer apparent. No contraction of the left frontalis muscle was visible, clinically, during the period in which the motor unit action potentials were being recorded.

going to recover with any degree of good function. A further electromyographic examination was carried out on April 24, 1944. At this time motor unit action potentials, a number of which were polyphasic, were obtained in all positions of the needle point in the right deltoid muscle in response to attempted movement. The activity was sufficient to obliterate one-quarter of the time-base tracing on the oscilloscope screen. Movements of the needle electrode in this case suggested that the fibres composing the motor units were not widely separated. Fibrillation action potentials were also recorded, but in reduced numbers. Some voluntary movement had returned. A similar picture was encountered in the left supra- and infra-spinatus muscles. The findings in this case suggested that the ultimate degree of recovery would be good.

The next case shows the use of electromyography as a routine investigation illustrating its value in diagnosis and prognosis following resection and suture of an interrupted peripheral nerve.

Pte. E. C. M., aged 26, was admitted to a Military Hospital on August 25, 1943, complaining of weakness of the right arm. He gave the following history. On June 29, 1943, as the result of a motor cycle accident, he sustained a severe head injury with a post-traumatic amnesia of forty-eight hours, and considerable bruising of his right arm. He made a slow recovery from his head injury but his right arm remained weak. On examination on August 25, 1943, he was found to have a paralysed right biceps and a weak right brachialis muscle. He also had sensory loss to all modalities over an area corresponding to the right musculo-cutaneous nerve. A sweating test on September 17, 1943, showed an isolated and complete lesion of the sudo-motor fibres in the musculo-cutaneous nerve. Electromyograms on the same date showed fibrillation action potentials only, in the biceps, coraco-brachialis and medial portion of the brachialis anterior muscles. The lateral portion of the brachialis muscle showed motor unit activity only. No other muscles in the right upper extremity or shoulder girdle showed any evidence of denervation. In view of these findings the diagnosis was a complete interruption of the right musculo-cutaneous nerve, although the mechanism of the injury was difficult to understand. At operation on September 21, 1943, a hard neuroma involving the origin of the musculo-cutaneous nerve from the lateral cord of the brachial plexus was excised and an end-to-end anastomosis effected. Electromyographic recordings were made at intervals after operation. On November 14, 1943, the first motor unit action potentials were recorded from the coraco-brachialis muscle; many were highly polyphasic. No motor unit action potentials were recorded from the long head of biceps or the medial half of the brachialis muscle, and the fibrillation activity was still vigorous. Within two weeks motor unit action potentials were recorded from all the previously paralysed muscles and a flicker of contraction was obtained. The prognosis was thus considered to be good. On January 2, 1944, there was good power in the right biceps muscle and electromyographic recordings from all the previously paralysed muscles showed vigorous motor unit activity and only a few fibrillation action potentials in all positions of the needle point. Observations on the form and amplitude of single motor unit action potentials during movements of the electrode in the recovered right biceps muscle suggested that the motor units were in many cases composed of widely scattered muscle fibres. The amplitude of the action potentials varied over a wider range than in the opposite normal biceps muscle.

The influence of prostigmin on neuromuscular transmission.—As observed in the description of our experimental case, the number of

involved. The majority fall into two clear-cut groups. The first are due to direct and indirect trauma, and the second to factors presumably causing pressure which in turn leads to ischæmia of the nerve trunk in its course through the temporal bone. Under the latter heading we have included paralysis following such conditions as "Bell's palsy," herpes zoster (we do not imply that ischæmia is the only underlying pathology in herpes zoster involving the facial nerve (*see* Denny-Brown *et al.*, 1944)), and otitis media.

Table II summarizes our findings in the traumatic group. Cases were most commonly referred to us when the prognosis from the clinical point of view was doubtful, or if recovery was delayed, but we have also selected other cases to illustrate our observations and to represent different types of lesion. Reference to Table II suggests that facial nerve paralysis following a closed head injury is due to ischæmic block rather than denervation in the majority of cases (Cases 1 to 6), which is in accord with Turner's observation (1944) that the prognosis in facial nerve paralysis following a closed head injury is good. In Cases 5 and 6, although no denervation was present, some weakness had persisted for a considerable period. This suggests that a decompression operation would be a logical step in a severe case with similar electromyographic findings (however, *see* Case 16, Table III). Cases 7 to 10 show that a varying number of axons may be completely interrupted in a closed head injury, in which case the prognosis is less favourable. In our series, recovery occurred in every case which we followed, but associated movements developed and the results were thus disappointing.

With regard to direct trauma, the prognosis naturally varies with the severity of the injury; in the cases in Table II regeneration was good, but associated movements appeared and gave disappointing results. Case 13 is of importance, for it suggests that in patients with complete axonal interruption following direct trauma, and without evidence of gross displacement of the nerve, six months at least should intervene before exploration and grafting are considered. It is in such cases that electromyography is valuable for detecting minimal re-innervation before the return of functional recovery. In Cases 11 and 12, earlier operation was justified in view of the X-ray findings of fracture and displacement of the mastoid tip. Case 11 suggests that treatment (physiotherapy) after grafting is of great importance. Comparing Cases 13 and 16, it seems doubtful whether the operation of nerve decompression is of value in promoting re-innervation. Turner's findings, that the prognosis in facial paralysis following closed head injury is so good, makes early decompression quite unwarrantable in this group of cases.

We have had similar results in other cases, and Wolf (1938) has already claimed that recovery of paralysis of lower motor neuron origin can be facilitated by cholinergic drugs.

(3) *Summary.*

(1) During the course of re-innervation, a decrease in the number of fibrillation action potentials recorded is observed before the return of motor unit activity.

(2) A variable time after the decrease of fibrillation activity, motor unit action potentials are recorded in response to attempts to move the paralysed muscles. The motor unit action potentials first appear close to the position of entry of the nerve into the muscle and spread from this area. As motor unit activity increases fibrillation activity decreases.

(3) When motor unit action potentials first make their appearance, they are small and often difficult to distinguish from fibrillation action potentials, especially in muscles which are capable of delicate movements such as those of the face.

(4) The range of amplitude and duration of motor unit action potentials from re-innervated muscles is greater than in corresponding normal muscles.

(5) There is a variable interval between the appearance of motor unit action potentials and the commencement of detectable functional recovery.

(6) Small highly polyphasic motor unit action potentials are usually obtained from re-innervated muscle and their detection is of value from a diagnostic point of view. They are most numerous in the earliest stages of regeneration, but may be obtained for over eighteen months after re-innervation.

(7) When motor unit action potentials first appear they cannot be sustained by voluntary effort.

(8) Experiments are described which suggest that regenerated motor units are composed of scattered muscle fibres. The scatter is least obvious in lesions of nerves in continuity.

(9) Evidence is brought forward which suggests that prostigmin facilitates neuromuscular transmission in the early stages of re-innervation.

VIII.—Case Records Illustrating the Results of Electromyographic Investigations in Some Specific Neurological Affections.

(1) *Facial Nerve Paralysis.*

We have now examined electromyographically more than seventy-five cases of facial nerve paralysis in which the lower motor neuron has been

(8) P/O. P. aged 22	Oct. 14, 1942 Closed head injury	Aug. 23, 1943 Complete at time of onset. Recovery delayed for some months	Occasional fibrillation action potentials in lower lip only; elsewhere reduced motor unit activity. Numerous small polyphasic action potentials	Recovery incomplete; associated movements severe
(9) Cpl. W. aged 32	Nov. 1, 1942 Closed head injury	Feb. 24, 1943 Complete at time of onset. Good recovery physiologically but associated and "tic" movements conspicuous	Reduced motor unit activity. Many polyphasic motor unit action potentials. No fibrillation activity	Regeneration had occurred following nerve interruption
		April 22, 1943 Ditto	Full motor unit activity; no fibrillation. Spontaneous motor unit discharge Polyphasic motor unit action potentials	Contracture and spontaneous twitching had commenced
(10) Miss C. aged 18	July 30, 1943 Closed head injury	Sept. 27, 1943 Complete	Fibrillation action potentials only	Complete axonal interruption. Subsequent course unknown. Prognosis poor. Recovery by regeneration. Associated movements certain
		Oct. 28, 1943 Ditto	Ditto	
		DIRECT TRAUMA		
(11) Sgt. F. aged 25	Mar. 2, 1943 Shell splinter wound mastoid region. Mastoid tip fractured and displaced	June 6, 1943 Complete	Fibrillation action potentials only	Nerve found divided at operation on July 4, 1943. Graft inserted
		July 4, 1943 Ditto	Ditto	
		Feb. 3, 1944 Still complete	Very little electrical activity. One polyphasic motor unit action potential; a few fibrillation action potentials	No treatment since operation. Contracture and fibrosis taking place
(12) Maj. J. aged 29	Nov. 1, 1943 Shell splinter wounds mastoid region. Mastoid tip fractured and displaced	Mar. 25, 1944 Complete	Fibrillation action potentials only	At operation, nerve found to have been crushed by indriven bone just above stylomastoid foramen
(13) Maj. K. aged 36	Jan. 28, 1943 Shell splinter wounds mastoid region	April 22, 1943 Complete	Fibrillation action potentials only	These results emphasize the importance of conservative measures for at least six months
		July 29, 1943 Complete	Fibrillation action potentials throughout, also a number of small highly polyphasic motor unit action potentials	
		Sept. 2, 1943 Excellent movements, but all of associated type	No fibrillation, vigorous motor unit activity throughout, many polyphasic motor unit action potentials	

TABLE II

Case, sex and age	*Date of onset and cause of paralysis*	*Degree of paralysis clinically*	*Electromyographic findings*	*Comments*
		CLOSED HEAD INJURIES		
(1) A.C.W.1 C. aged 32	Sept. 26, 1943 Closed head injury	Oct. 11, 1943 Slight weakness only. Paralysis not observed for 5 days following injury	Reduced normal motor unit activity only	Recovery complete by Oct. 26, 1943
		Oct. 26, 1943 Complete recovery	No abnormality detected	
(2) W.R.P. H. aged 58	Jan. 16, 1943 Closed head injury	Feb. 4, 1943 Slight weakness only	Reduced normal motor unit activity. No fibrillation action potentials	Recovery complete clinically by Mar. 20, 1943
		Feb. 20, 1943 Improved	Increase in motor unit activity. No fibrillation action potentials	
(3) Dvr. P. aged 19	June 1, 1943 Closed head injury	June 14, 1943 Severe but incomplete. Onset 2 days following injury	Reduced normal motor unit activity. No fibrillation action potentials	Recovery reported complete clinically Sept. 1943. (Earliest date of recovery unknown)
(4) L.A.C.W. W. aged 22	Sept. 3, 1943 Closed head injury	Sept. 10, 1943 Complete. Onset delayed for 3 days	Motor unit action potentials on insertion of needle only	Reversible ischæmic block. Complete clinical recovery in 8 weeks
		Nov. 3, 1943 Complete recovery	No abnormalities from electromyographic point of view	
(5) Sign. H. aged 21	Jan. 20, 1943 Closed head injury	May 6, 1943 Slight weakness only	Reduced normal motor unit activity. No polyphasic motor unit action potentials. No fibrillation action potentials	Findings suggest prolonged ischæmic block as the pathological basis of the findings
(6) A.C.2 P. aged 21	July 12, 1942 Closed head injury	Feb. 4, 1943 Slight weakness only No associated movements Complete at first but recovered to present degree 11–12 weeks later	Reduced normal motor unit activity only. No fibrillation action potentials or polyphasic motor unit action potentials	Findings suggest prolonged reversible ischæmic block
(7) Pte. O. aged 27	Oct. 26, 1943 Closed head injury	Dec. 13, 1943 Complete	Fibrillation action potentials throughout and some motor unit action potentials on insertion of electrode. In forehead 1 motor unit action potential. In cheek, including lips, 2 motor unit action potentials in response to attempted movement	*Prognosis:* good, probably few associated movements It was reported on Feb. 1, 1943 recovery taking place, face now only weak on affected side

TABLE II—*cont.*

Case, sex and age	*Date of onset and cause of paralysis*	*Degree of paralysis clinically*	*Electromyographic findings*	*Comments*
(14) Pte. W. aged 28	July 8, 1944 Mortar shell wound mastoid region	July 20, 1944 Complete	Repetitive fibrillation action potentials only, few in number. Many fibrillation action potentials on insertion of the electrode. No motor unit action potentials	Complete axonal interruption. It is interesting that repetitive fibrillation action potentials were recorded as early as 12 days from date of injury. Faradic response absent
		INJURY TO THE NERVE DURING THE OPERATION FOR MASTOIDECTOMY		
(15) Mrs. J. aged 35	April 16, 1943 Following radical mastoidectomy	April 29, 1943 Complete	Very few motor unit action potentials on insertion of the needle only	This patient evidently had a complete axonal interruption. Treatment by massage and galvanism was regular and vigorous
		May 6, 1943 Complete	Fibrillation action potentials only throughout	
		June 17, 1943 Complete	Ditto	
		July 15, 1943 Complete	Occasional small highly polyphasic motor unit action potentials, fibrillation action potentials throughout	
		July 29, 1943 Feeble associated movements	Decrease in fibrillation, increase in motor unit activity	
		Sept. 9, 1943 Vigorous associated movements, face symmetrical in repose	Vigorous motor unit activity, a few tonic motor unit action potentials, occasional fibrillation action potentials	
		Dec. 30, 1943 Marked spasm and fasciculation. Vigorous movements	Many tonic and fasciculating motor unit action potentials	
(16) Gnr. P. aged 31	Oct. 13, 1942 Following operation for radical mastoidectomy	Jan. 20, 1943 Complete	Motor unit action potentials on insertion of the needle only. No fibrillation action potentials	Ischæmic block
	Oct. 14, 1942 Nerve decompressed. Reported to be swollen only	Feb. 2, 1943 Complete	Fibrillation action potentials throughout. One motor unit action potential under voluntary control. A few motor unit action potentials on insertion of the needle	Denervation and some ischæmic block. Condition deteriorating
		Feb. 23, 1943 Complete	Fibrillation action potentials only	Denervation complete
		April 19, 1943 Complete	Fibrillation action potentials throughout. 2 highly polyphasic motor unit action potentials	Re-innervation commencing

		May 27, 1943 Slight associated flickers of movement	Decrease of fibrillation and increase of motor unit activity	
		Aug. 19, 1943 Good associated movements, face symmetrical in repose	Ditto	
		Feb. 2, 1944 Spasm and occasional clonic twitches. Movements vigorous, associated in type	No fibrillation action potentials Vigorous motor unit activity. Tonic motor unit action potentials, many polyphasic motor unit action potentials. Some fasciculation motor unit action potentials	Recovery, but movements all of associated type
(17) L/Cpl. B. aged 28	Mar. 4, 1943 Following radical mastoidectomy	June 8, 1943 Complete	Fibrillation action potentials throughout, also many motor unit action potentials on insertion of the needle	After prostigmin slight voluntary contractions
		July 19, 1943 Voluntary movements returning; movements not associated	Less fibrillation. Increased motor unit activity. Many action potentials very polyphasic	Case not followed further. Prognosis considered good
(18) Miss A. aged 60	Dec. 15, 1942 Following radical mastoidectomy	May 10, 1943 Said to be complete at first	Fibrillation action potentials throughout, in addition to many motor unit action potentials throughout, some very polyphasic	Prognosis considered good. Case not followed

TABLE III

FACIAL NERVE PARALYSES OF INFECTIVE ORIGIN

Case sex and age	*Date of onset and cause of paralysis*	*Degree of paralysis clinically*	*Electromyographic findings*	*Comments*
(1) Mr. B. J. aged 22	Nov. 25, 1942 Bell's palsy	Dec. 27, 1942 Complete	No fibrillation. Motor unit action potentials only on insertion of the needle	Prognosis good. Reversible ischæmic block
		Jan. 12, 1943 Complete	A few repetitive motor unit action potentials in region of upper lip when patient attempted to whistle. No fibrillation action potentials	Recovery commencing
		Feb. 26, 1943	Full motor unit activity. No fibrillation action potentials	Complete clinical recovery

TABLE III—*cont.*

Case sex and age	*Date of onset and cause of paralysis*	*Degree of paralysis clinically*	*Electromyographic findings*	*Comments*
(2) Mr. V. A. aged 43	June 29, 1943 Bell's palsy	July 19, 1943 Incomplete (Complete at first)	Fibrillation action potentials throughout, but also 2-3 motor unit action potentials	Prognosis good, but some associated movements
		July 30, 1943 Incomplete	Ditto	Not followed
(3) Gdsm. L. aged 31	Mar. 7, 1943 Bell's palsy	Mar. 29, 1943 Complete	Fibrillation action potentials only	Complete denervation. If regeneration occurs, associated movements probable
(4) L.A.C. M. aged 28	Sept. 12, 1943 Bell's palsy	Dec. 13, 1943 Complete at onset	Fibrillation action potentials throughout. 3-4 motor unit action potentials on attempted movement, many small and highly polyphasic	Evidence of commencing regeneration, clinical and electromyographic. Prognosis apart from associated movements good
(5) Pte. T. aged 24	Feb., 1942 Bell's palsy	Aug. 19, 1943 Complete at onset	Occasional fibrillation action potentials. Motor unit activity vigorous (½ time base tracing) but many small highly polyphasic motor unit action potentials	Blink reflex poor, but recovery has occurred to some extent. All movements associated. Treatment sporadic
(6) Mrs. F. aged 58	Sept. 30, 1943 Following herpes	Oct. 21, 1943 Complete for one week. Now improving steadily	Vigorous motor unit activity. Very occasional fibrillation action potential	Prognosis considered excellent
(7) Pte. W. aged 30	Dec. 3, 1943 Following herpes	Dec. 17, 1943 Complete	Fibrillation action potentials only on insertion of the electrode. A few motor unit action potentials, some in response to attempted movement	Prognosis given as good, but probably some associated movements
		Jan. 4, 1944 Complete	Now numerous repetitive fibrillation action potentials, otherwise as above	
		Jan. 20, 1944		
		Feb. 3, 1944	Similar findings	
		Mar. 6, 1944 Complete		
		April 8, 1944 Flicker of movement	Increase in number of motor unit action potentials, some small and highly polyphasic	
		June 12, 1944 Excellent movements	No fibrillation action potentials. Full motor unit activity, some small polyphasic motor unit action potentials	Some associated movements but blink reflex fair. Recovery satisfactory

(8) Mr. C. C. aged 69	Sept. 4, 1943 Following herpes	Sept. 30, 1943 Complete	Fibrillation action potentials only	Prognosis as regards recovery considered to be good. Associated movements probably complete
		Oct. 11, 1943 Complete	2 motor unit action potentials (in response to attempted movement) in forehead only	
		Nov. 8, 1943 Complete	Ditto	
(9) Tpr. K. aged 25	May 30, 1943 Following herpes	Aug. 19, 1943 Complete initially	Vigorous motor unit activity throughout. Fibrillation action potentials occasional in lower lip only. Many small highly polyphasic motor unit action potentials	Movements fair, only moderate amount of associated movement. Blink reflex poor
		Oct. 20, 1943 Improved	As above but no fibrillation action potentials	Great clinical improvement. Blink reflex fair
(10) Mrs. G. aged 58	Jan. 26, 1943 Following herpes	Mar. 2, 1943 Complete	Fibrillation action potentials only	Prognosis doubtful
		April 19, 1943 Complete	Fibrillation action potentials throughout. 1-2 motor unit action potentials also recorded	Prognosis good as regards recovery but associated movements likely to be severe with possible spasm or tic
(11) Mrs. R. aged 22	Oct. 19, 1943 Following an attack of earache	Nov. 26, 1943 Partial	Reduced normal motor unit activity only	Reversible ischæmic block, prognosis good
(12) Mr. W. T. aged 60	April 27, 1943 Associated with otitis media	May 6, 1943 Complete	1-2 motor unit action potentials in response to attempted movement. Motor unit activity on insertion of the electrode	Too early to give a prognosis but degeneration is not complete
	Ear improving	May 30, 1943 Partial	Increased motor unit activity, no fibrillation action potentials	Face recovering
		May 27, 1943	Occasional fibrillation action potentials in lower lip. Increased motor unit activity throughout	Face recovering
	Ear no change	June 3, 1943 Stationary	Fibrillation action potentials throughout. Motor unit activity remains the same ($\frac{3}{4}$ obliteration time base tracing)	Face still weak. No further improvement
		June 17, 1943 Ditto	No change	Clinically no change
		July 15, 1943 Improved	Increase of motor unit activity	Improving clinically
	Ear condition much improved	Aug. 5, 1943 Improved	Great increase of motor unit activity, decrease of fibrillation activity	Great improvement clinically Associated movements not severe

TABLE III—*cont.*

Case sex and age	*Date of onset and cause of paralysis*	*Degree of paralysis clinically*	*Electromyographic findings*	*Comments*
(13) Mrs. J. R. aged 22	Aug., 1939 Following conservative mastoidectomy	June 17, 1943 Almost complete	Vigorous fibrillation action potentials throughout.	Slight twitch in lower lip on voluntary effort
	Nov. 23, 1939 Gross infection. Radical mastoidectomy. Splinter of bone transfixing nerve removed		Occasional small highly polyphasic motor unit action potentials in lower lip	
		Feb. 16, 1944 Almost complete	A slight increase in motor unit activity in lower lip region only	Slight increase in contraction in lower lip possible
	Nov. 1940 Damaged nerve excised and grafted (lateral cutaneous nerve, thigh). Some infection followed but wound healed in 2 months	June 22, 1944 Almost complete	No change. Fibrillation activity as vigorous as ever	Has had vigorous massage and galvanic treatment from onset of paralysis
(14) Mrs. C. aged 28	1938 Following otitis media	July 13, 1944 Complete	Vigorous fibrillation activity only in all positions of the needle	Complete axonal interruption. Has had continuous and vigorous physiotherapeutical treatment since onset of paralysis
(15) Miss G. aged 22	1937 Gradual onset following discharging ear	May 4, 1943 Complete in three months	No fibrillation action potentials in any position. Motor unit action potentials on insertion of the electrode and 1-2 normal motor unit action potentials on attempted movement	Ear still discharging. Pus soaked wool removed from region of facial canal. No contracture of face. Feeble faradic response obtained. A case of prolonged ischæmic block. Report by letter, Jan., 1944, ear still discharging. Face remains paralysed.

TABLE IV

MISCELLANEOUS GROUP OF FACIAL NERVE PALSIES

Case Sex and age	*Date of onset and cause of paralysis*	*Degree of paralysis clinically*	*Electromyographic findings*	*Comments*
(1) Cpl. F. aged 24	14 years ago Cause unknown	May 27, 1943 Incomplete Complete at first	No fibrillation action potentials. Many areas from which no electrical activity was recorded. 2-3 motor unit action potentials	Face symmetrical in repose. Movement poor and of associated type. A case where re innervation has been partial and a number of muscle fibres undergone fibrosis. No treatment
(2) Mr. G. P. aged 18	12 years ago Birth palsy	Mar. 10, 1944 Incomplete Complete at first	No fibrillation action potentials. Many areas from which no electrical activity was recorded. 2-3 motor unit action potentials	Face symmetrical in repose. Movement poor and of associated type. A case where re-innervation has been partial and a number of muscle fibres undergone fibrosis. No treatment
(3) Mr. D. T. aged 29	28 years 6 months ago Following mastoid operation at age of 6 months	Dec. 27, 1942 Complete	No electrical activity whatever recorded	Face symmetrical in repose, no blink reflex or movement. Galvanic response absent. Ectropion has improved since childhood. Muscle completely replaced by fibrous tissue. No treatment
(4) Pte. McH. aged 35	July, 1943	Feb. 11, 1944 Incomplete	Vigorous motor unit activity in frontalis muscle with occasional fibrillation action potentials and a few small highly polyphasic motor unit action potentials. In cheek muscles there was little electrical activity, but in some places fibrillation action potentials were recorded and also some small highly polyphasic motor unit action potentials	Forehead movements fair, rest of face paralysed. The consultants' diagnosis was " possibly infiltrating glioma of pons in view of other minimal signs." Electromyographic findings suggest partially re-innervated facial musculature

It is not possible by electromyography to distinguish between a total axonal interruption and a complete ischæmic block for some days after the injury. Case 15 (Table II) shows that such differentiation may not be possible until thirteen days have elapsed, but in Case 14 repetitive fibrillation action potentials were recorded twelve days after the onset of the paralysis. In no case of facial nerve paralysis which we have examined has the onset of fibrillation exceeded fourteen days. In view of the effect of temperature on fibrillation it is of some interest to note that in Case 15 (over thirteen days) the paralysis occurred in the spring (April) whereas in Case 14 (twelve days) the onset of the paralysis was in July, a warmer month than April. A few nerve fibres often escape damage, even if the paralysis is complete clinically, and the demonstration of even a single repetitive motor unit action potential is of great prognostic significance (Case 7). Duel (1936) has stated that the electrical reactions give valuable information as to the severity of the paralysis at a very early date, and that the faradic response has usually disappeared in forty-eight to seventy-two hours in severe cases of nerve lesion. Unfortunately we have not, so far, had an opportunity of comparing our electromyographic observations with the electrical reactions except in two or three cases, but we are now analysing a series of cases from this point of view. If Duel's claims are universally applicable, a combination of both types of examination should be invaluable. We have found, however, in the few cases which we have examined, that the faradic response may be difficult to assess and is a somewhat painful procedure; moreover, in a case quoted by Duel, the electrical reactions showed a reaction of degeneration nine weeks after the onset of paralysis but, following an operation of decompression, the faradic response returned, and within a month the patient had recovered. Clearly in this case the electrical reactions were misleading. The condition must have been one of reversible ischæmic block and not axonal interruption, for regeneration proceeds at a slower speed than could be accounted for in this case.

In Table III are set out our observations on a selected number of cases from the infective group. We have not included many cases of Bell's palsy, for our findings in the great majority of these cases were quite unspecific. In mild cases there was a reduction in motor unit activity in response to a maximum effort to move the muscles, but no other abnormalities. Clinical and electromyographic recovery was the rule within a few weeks. It is clear that in this group, as in the last, our electromyographic findings parallel the clinical observations, but in addition offer a more detailed analysis of the nature of the paralysis. A precise picture of the condition in facial nerve paralysis is particularly valuable in pro-

gnosis, for we have shown in Tables II and III that, where there is a considerable degree of lower motor neuron denervation, recovery when it takes place is always disappointing because of the occurrence of associated movements. It seems clear that following complete axonal interruption, whatever the cause of the interruption, or whether displacement has taken place or not, recovery is by an haphazard outgrowth of nerve fibres which do not follow their original pathways and in which dichotomization is common. The work of Howe, Tower and Duel (1937) has placed the phenomena of associated movements and facial tic following regeneration on a sound anatomical and physiological basis and, as pointed out by Turner (1944) the ultimate prognosis is poor as regards overcoming these complications in view of the mode of recovery by dichotomy. Ballance and Duel (1932) have advocated that immediately a facial paralysis is recognized the nerve should be decompressed to prevent axonal interruption, but, in view of the work of Denny-Brown and Brenner (1944*a*), it does not seem likely that many operations could be carried out in time to be effective, and clearly the majority would be unnecessary. In addition, it is doubtful from the anatomical point of view, whether exposure of the nerve in the facial canal and slitting its sheath is an effective method of decompression. Kettel (1943) analysed a large number of cases of facial nerve paralysis associated with otitis media or mastoid infection from the point of view of the optimum time for operation, but came to no definite conclusions. He was, however, of the opinion that in cases of immediate complete facial nerve paralysis following mastoidectomy or labyrinthectomy the facial nerve should be explored within seventy-two hours. We have not examined enough cases to make any statement on this point, but our limited experience suggests that the operation of decompression is of theoretical rather than practical value (compare Case 16, Table II, and Case 15, Table III). Case 15, Table III, is of great interest, for it suggests that ischæmic block may persist for an unlimited period. The fact that a faradic response was still present was fortunate, for it served to confirm the electromyographic observations. It is in such a case as this that recovery might be expected to follow decompression comparable to the case quoted from Duel on p. 238, but, it is possible that the persistence of infection prevented recovery taking place.

In Table IV are reported our findings in three cases of very long-standing paralysis. The contracture was confirmed as being due to fibrous metaplasia, for there were numerous areas of electrical "silence" in the facial muscles. It is also noteworthy that these patients received no physiotherapeutical treatment. They can be compared with Case 11,

Table II, and are in sharp contrast to Case 15, Table II, and Cases 13 and 14, Table III.

(2) *Intrinsic Laryngeal Paralysis.*

We have made electromyographic recordings from the intrinsic muscles in seven cases, four of which are reported here.

Case 1.—This patient was a woman, aged 27, who developed symptoms and signs of hyperthyroidism early in 1942. A partial thyroidectomy was performed on July 25, 1942, following which she had a bilateral abductor palsy of the vocal cords resulting in a difficult convalescence. Six weeks after the operation she was discharged but still had difficulty in breathing and there was a marked expiratory stridor. She improved very slowly. On June 15, 1943, a direct laryngoscopy revealed a flicker of abduction in both vocal cords. Electromyographic recordings from the muscles on both sides of the larynx showed a continuous stream of motor unit action potentials of all shapes and sizes, resembling most closely those found in facial musculature. The number of action potentials waxed and waned with the respiratory excursion (maximum outburst on inspiration) but at no time was there an absence of electrical activity. The number of action potentials was less than that usually recorded from normal facial musculature and it was possible to see individual motor unit action potentials on the oscilloscope screen, the time base tracing of which was never more than half obliterated when the patient attempted to sustain a high-pitched note (Plate IX, fig. 7). Occasional polyphasic motor unit action potentials were seen. Owing to the constant motor unit activity it was not possible to determine whether there were any fibrillation action potentials. Since the examination indicated the presence of motor unit activity, even though reduced, a tracheotomy was decided against. On October 28, 1943, the patient was seen again. She had greatly improved and her voice and breathing were approaching normal. Direct laryngoscopy showed an increase in the ability to abduct the vocal cords. Electromyographic recordings showed an increase in the motor unit activity.

Case 2.—This patient was a soldier of the United States Army, aged 34. He gave the following history. In December, 1943, his friends told him that his breathing was loud at night. In February, 1944, he himself noticed that his respiration was noisy and that his voice was getting husky; he therefore reported sick and was admitted to a Military Hospital on May 11, 1944. On examination the following abnormalities were detected. His voice was husky and he had an expiratory stridor. There were a few jerks of nystagmus on lateral deviation of the eyes more to the right than the left. His tongue deviated slightly to the left and there was minimal weakness of the left palate and pharyngeal musculature. His tendon reflexes were slightly increased in the right arm and exaggerated in both lower extremities. Direct laryngoscopy showed bilateral abductor paralysis of the vocal cords. The tentative diagnosis was disseminated sclerosis. A tracheotomy was performed on May 20, 1944, from which the patient made a good recovery. On May 24, 1944, an electromyographic investigation was made (*see* Table V). The findings indicated lower motor neuron denervation of a severe degree affecting the abductor muscles of the vocal cords. The small highly polyphasic motor unit action potentials were difficult to account for; elsewhere they would have denoted re-innervation. It is possible that some re-innervation had taken place in this case.

Case 3.—This was a Lieutenant of the United States Army Air Corps, aged 28, who on February 15, 1944, was struck on the right side of the neck by a piece of

"flak." His voice was hoarse immediately after being struck. On examination on March 7, 1944, he had a small healed wound on the right side of the neck. An X-ray photograph showed a retained metallic foreign body in the posterior neck muscles. Its relation to the scar suggested that it must have passed close to the right recurrent laryngeal nerve. There were no other abnormal findings on physical examination. He still had a hoarse voice and a direct laryngoscopy showed a complete paralysis of the right vocal cord. Electromyographic recordings were made from both the normal and affected muscles. The findings are given in Table VI. The examination showed that complete axonal interruption of the right recurrent laryngeal nerve had occurred. It was clear that no return of cord movement could be expected until regeneration had taken place.

Case 4.—This was a man, aged 59, who complained of hoarseness of six months' standing. On examination on November 17, 1943, apart from the hoarseness no abnormal findings were encountered. X-rays of his chest were normal. Clinically he was labelled a recurrent laryngeal nerve paralysis of unknown ætiology. On direct laryngoscopy the left vocal cord was apparently completely paralysed. Electromyographic recordings, however, showed normal motor unit activity from all the muscles of both sides of the larynx. It was thus clear that the paralysis of the vocal cord was not due to interruption of the nerve supply of its muscles. Manipulation of the arytenoids was then attempted; the result suggested an ankylosis at the left crico-arytenoid joint.

The cases described above indicate that electromyographic recordings from the intrinsic laryngeal muscles may be of diagnostic and prognostic value in selected cases. It was noted during our recordings from the normal laryngeal muscles that the motor unit action potentials were small and sharp and resembled those recorded from the facial musculature. Moreover, in the cases with reduced motor unit activity, single isolated action potentials were observed and the slightest movement of the electrode reduced their amplitude almost to base level. It was also clear that the intrinsic laryngeal muscles have a resting "tone" due to motor unit activity, for it was not possible to obtain "electrical silence" by any manœuvre, including breath-holding. The waxing and waning of activity with each respiratory excursion has already been referred to, the amount of activity during expiration was more than might have been expected.

TABLE V

Muscle	*Electromyographic Findings* (Case 2)
Inter-arytenoids	Normal motor unit activity
Left thyro-arytenoid	Normal motor unit activity
Right thyro-arytenoid ...	Normal motor unit activity
Right crico-arytenoid Left crico-arytenoid	Fibrillation action potentials uninfluenced by respiratory movements. There were a few distant motor unit action potentials in a few positions of the needle. Three close small highly polyphasic motor unit action potentials were also recorded

TABLE VI

Muscle	*Electromyographic Findings* (Case 3)
Left lateral crico-arytenoid ...	Normal motor unit activity
Right lateral crico-arytenoid ...	Fibrillation action potentials only
Inter-arytenoids	Reduced motor unit activity. Fibrillation activity, if present, masked
Right posterior crico-arytenoid	Fibrillation action potentials, some distant motor unit activity

(3) *Spinal Cord Injuries and Diseases.*

We have now made a large number of electromyographic investigations in patients with spinal cord injuries and diseases. We have selected a few cases to illustrate specific points and to indicate the possible clinical value of the investigation.

Case 1. Spinal cord injury.—Gnr. L. R., aged 20, as the result of a motor cycle accident on June 29, 1942, sustained a fracture dislocation involving the 6th and 7th thoracic vertebræ, and a spinal cord injury which gave rise to symptoms and signs of a complete transverse lesion at the level of the 5th dorsal segment. Two days after his accident a suprapubic cystotomy was performed and permanent drainage of the bladder instituted. On examination at a Military Hospital on July 4, 1942, he had a complete flaccid paralysis below D.5 and sensory loss to all modalities below this level. His arms were normal in all respects. There was a feeble flexor plantar response as the result of vigorous stimulation of the soles of the feet. His urine was mildly infected but he was otherwise well. A lumbar puncture was performed and revealed a partial manometric block with the Queckenstedt test. A laminectomy was therefore decided upon, but the day following admission he had a high temperature (103° F.), his urine was heavily infected, and his sensory level had apparently ascended one segment. He was given sulphonamides. He did not improve, however, and three days later there were signs of consolidation at the base of the right lung. His sensory level had returned to its original position within twenty-four hours, but there was now no response on the most vigorous plantar stimulation. In view of his generally poor state of health, he was put in a plaster bed and operation postponed. During the next four weeks he gradually improved, his temperature settled, his urine became less infected, his abnormal chest signs disappeared, but his neurological condition was unchanged. It was decided that operation was unlikely to be of value at this stage. Thenceforward his general condition remained much the same except for occasional episodes consisting of rigors and high temperature due to urinary infection, which lasted about forty-eight hours before subsiding. On February 3, 1943, he still had a completely flaccid paralysis below D.5 with a corresponding sensory loss. The paralysed muscles were "toneless" but there was only moderate wasting. Electromyographic recordings were made from all the chief muscle groups in the lower extremities. No motor unit action potentials were recorded in any position of the needle point, but many repetitive fibrillation action potentials appeared. The findings indicated a lower motor neuron denervation of a severe degree, and it was inferred, in the light of Holmes' (1915) work and in view of the course the case had taken, that a large number of the anterior horn cells below the level of the lesion had been destroyed. In this connexion it may be noted that Tower (1941)

has shown conclusively in experimental animals that functional denervation through isolation of the spinal cord does not give rise to fibrillation. A sweating test performed on February 8, showed complete anhydrosis below D.10 with hypohydrosis between D.6-10. It was also observed that there was no sweat secretion over the lower extremities in response to local stimulation, either by warmth or by faradic coil. This suggested a very severe degree of cord destruction and the possibility of extensive vascular damage was postulated (Davison, 1933). The electromyographic investigations in this case were some guide to prognosis; the findings indicated that no return of reflex activity could be expected.

Case 2. Spinal cord injury.—A.T.C. Cadet M. L., aged 14, on May 3, 1942, was helping to beach a sea mine when he was struck by a machine-gun bullet from an aircraft. The bullet entered immediately behind the left shoulder and came out at a point in the back 2 in. from the mid-line opposite the 11th dorsal vertebra. He immediately fell to the ground and noticed that he was unable to move his legs and was numb below the level of the waist. He did not lose consciousness. On the way to hospital he had increasingly severe abdominal pain. On admission to an R.A.F. hospital the following points were noted: patient pale and shocked; pain in epigastrium, tender and rigid over this area; symptoms and signs strongly suggestive of intra-abdominal lesion in addition to hæmo-pneumothorax.

He was operated on within a short time of admission and the following notes were recorded: (1) 10 oz. of blood were aspirated from the left pleural cavity; (2) mid-line epigastric incision, abdomen opened but no evidence of any damage to viscera, no blood or free fluid. Diaphragm intact; (3) entry and exit wounds excised and sutured. The following day a lumbar puncture was done, when it became apparent that the patient was completely paralysed and anæsthetic below the 10th dorsal segment, and had retention of urine. The spinal fluid was deeply blood-stained and at a pressure of 150 mm. The next day his spinal column was X-rayed but nothing abnormal was seen. His general condition slowly improved, but from the neurological point of view there was no change. He was catheterized regularly. On May 19, 1942, he was transferred to a Military Hospital. On examination at this time he displayed symptoms and signs of a complete transverse lesion of the cord at the level of D.10 segment. His paraplegia was flaccid, but on powerful stimulation of the soles there was a minimal plantar flexion response. There were two large decubitus ulcers, one over each buttock. Apart from this, his general condition was good. Stereoscopic X-rays showed a small fragment of bone depressed from the posterior arch of the left 10th dorsal vertebra.

On June 26, 1943, examination showed a healthy, well-covered, growing boy; two large decubitus sores over the buttocks had healed well, and there was no evidence of urinary infection, and the bladder was now voiding urine reflexly. No neurological abnormalities were detected above a segmental level of D.10. Below this level there were symptoms and signs of a complete interruption of the spinal cord. A flexion reflex could be evoked by noxious stimulation of the sole. He voided his urine at irregular intervals, often following vigorous involuntary flexion movements of the lower extremities. The knee-jerks were brisk and the bulbocavernous, cremasteric, and abdominal reflexes could all be elicited. He had an erection and seminal emission if a mass reflex was evoked, and on occasions he became drenched in sweat below the level of the lesion. It was found difficult to elicit the ankle-jerks and ankle clonus was somewhat difficult to initiate and maintain. It was also apparent that the hamstrings and leg muscles were proportionately smaller than the quadriceps and adductor muscles. Finally, it was noted that a greater noxious stimulus was required to

elicit a flexion reflex when the field of application was the skin over the dorsum of the right foot as compared with the left, and both areas had a greater threshold than the skin over the front of the thighs. Electromyographic recordings were made from all the chief muscle groups below the level of the lesion. In the muscles supplied by the sciatic nerve only, a number of fibrillation action potentials were recorded from all positions of the needle point; the greatest fibrillation activity being recorded from the left lateral popliteal group. There was motor unit activity also on insertion of the needle and during reflex spasms. In addition, it was possible to demonstrate the presence of a crossed extensor reflex electromyographically, a phenomenon less convincing clinically. The quadriceps and adductor muscle groups showed no fibrillation action potentials. A sweating test paralleled our electromyographic findings, for there was hypohydrosis on both sides over the area of sciatic distribution. Thus for some reason this patient had a partial bilateral sciatic nerve lesion in addition to a complete transverse lesion of the spinal cord. We tentatively put forward the suggestion that this might have been caused by repeated intermittent trauma of bed-pans pressing on the sciatic nerves, for owing to the spinal cord lesion such traumata would be unrecognized by the patient. The decubitus sores may also have been concerned in the ætiology.

These two cases illustrate the value of electromyography in detecting lesions of the lower motor neuron in cases with spinal cord lesions. We do not claim that without this investigation the condition cannot be recognized, for a careful clinical examination in the cases described clearly revealed the signs of a partial lower motor neuron denervation of the distribution found electromyographically. In cases with minimal lesions, however, the investigation has proved a most useful diagnostic aid. In a recent paper, Lewin (1943) has indicated the value of electromyography in the diagnosis of minimal pressure palsies in paralysed limbs, although, of course, if the lesion is in any way disabling, it can be determined by clinical examination.

Case 3. "Motor neuron" disease.—L.A.C. T., aged 34, was admitted to a Military Hospital on April 19, 1944. He gave the following history. About September, 1943, he noticed that he was getting clumsy with his left hand and that his grip would tire easily if he had to hold heavy objects with it for any length of time. His symptoms gradually got worse over the next six months and he noticed that his right hand was getting weak and that his left hand was getting thin. He also remarked that he had difficulty in keeping his left little finger straight. On examination his left hand was in a typical "main en griffe" attitude during repose and there was severe wasting and weakness of all the intrinsic muscles. The left extensor carpi radialis longus muscle was a little weak and fasciculations were noticed in it in addition to a number in the intrinsic muscles of the hand, particularly the first dorsal interosseus muscle; apart from this no wasting or weakness of either arm or forearm muscles was detected. On the right side, fasciculations and some weakness were detected in the triceps muscle. The intrinsic muscles of the hand were also somewhat weak but no fasciculations were observed. There was no sensory involvement or sweating change. No abnormalities were detected in the spinal fluid and the Wassermann and Kahn reactions in blood and cerebrospinal fluid were negative. X-rays of the cervical

spine and thoracic inlet were normal. The clinical diagnosis was "motor neuron" disease. Electromyographic investigations on May 4 and June 1, 1944, showed findings typical of those we have found in other cases of motor neuron disease. When the needle electrode was inserted into a fasciculating portion of an affected muscle, the action potentials appeared to be similar to those from normal motor units, but there was often synchronous firing of the action potentials in and slightly out of phase. Sometimes the action potentials were very large and resembled a tetanic twitch; such appearances, however, were always associated with coarse fasciculation twitches around the electrode. Fibrillation action potentials were recorded in varying numbers depending on the degree of wasting of the muscle being sampled; for instance, from the right triceps muscle only a few were recorded, while from the left first dorsal interosseus muscle a large number were obtained in all positions of the needle point. The most characteristic findings, however, were obtained on insertion of the needle. This provoked an outburst of large high-frequency action potentials which gave rise to musical notes and were very similar to the action potentials provoked in the same way from muscles in cases of myotonia congenita except that they were less numerous and less widespread through the muscle (Plate IX, fig. 6).

In three cases of "motor neuron" disease we have blocked the nerve to the affected muscles and obtained complete motor, sensory and vasomotor paralysis. The electromyographic findings, however, remained the same as before the block and similar to those described above. The visible fasciculations continued despite the nerve block, a finding similar to those reported by Grund (1938), and Forster and Alpers (1944), who conclude that the fasciculations seen in "motor neuron" disease and infectious polyneuritis are not affected by spinal anæsthesia or peripheral nerve block. In addition, prostigmin increases the fasciculations, while curare abolishes them and prevents their induction by prostigmin.

There can be no doubt therefore that the fasciculations observed originate in the region of the myoneural junction. This accounts in part for the similarity between our findings on insertion of the needle electrode in "motor neuron" disease and myotonia congenita. The presence of repetitive fibrillation action potentials is peculiar to "motor neuron" disease, however, and is indicative of the degree of denervation.

It seems possible that the slowly progressive degenerative change in the anterior horn cell in "motor neuron" disease influences the myoneural junction, but the nature of the influence is unknown. It is of great interest that motor unit action potentials similar to those obtained from fasciculating muscles can sometimes be obtained from patients with slowly progressive peripheral nerve lesions. This suggests that the myoneural junction changes are not directly related to pathological changes specifically associated with the anterior horn cell but to slowly progressive degenerative changes initiated anywhere along the neuraxon.

The value of electromyography in diagnosis in "motor neuron" disease

is undoubted, but only in combination with a clinical examination can the diagnosis be established. Electromyography may prove to be of greater value than it is at the moment, for in patients with a clinical picture of "motor neuron" disease apparently normal muscles give rise to high-frequency action potentials on insertion of the needle electrode, and such a picture may be indicative of the disease in the earliest stages. At the moment, however, such action potentials can only be regarded as indicative of changes at the myoneural junction.

(4) *Sciatica.*

We have now examined electromyographically the muscles of the lower extremities in over 50 cases of sciatica due to various causes. We have found that, in cases where muscle wasting and weakness are displayed, the investigation is of diagnostic value, for the wasting is due to two major causes in such cases, denervation and disuse, and by clinical examination alone it is difficult to assess the proportion of wasting attributable to each cause. Expert clinicians, however, have usually predicted the result of our electromyographic findings accurately. In addition to detecting the presence of lower motor neuron denervation, we have made some observations which we believe throw some light on slowly progressive denervation due to damage at any point along the course of the lower motor neuron.

Sciatica due to prolapsed intervertebral disc : Case 1.—Pte. R. F., aged 20, was admitted to a Military Hospital on May 12, 1943. He gave the following history. Three years before admission he fell down a steep bank and injured his back slightly, but within twenty-four hours was symptom free. One month later, following a fit of coughing, he had a severe pain in his right buttock and his right leg "went stiff." He got some relief by lying on the affected side but, after this initial relief, the pain in his buttock did not pass off to any great extent despite rubbing with liniment. The stiffness went out of his leg, however, but left an unpleasant ache. His pain was continuous from the onset but made worse by coughing, standing, or sitting down. He was treated at a number of places by rest and splintage, at others by massage, radiant heat and other physio-therapeutical measures without any lasting relief. In June, 1942, he was operated on for the removal of a prolapsed intervertebral disc, but the exploration was negative. A further exploration in August, 1942, following a severe meningeal reaction and exacerbation of symptoms, a sequel to intrathecal lipiodol myelography, was also negative. His pain did not get any better and he noticed that his right thigh muscles were weak after the second operation. A further course of rest and physiotherapy was advised, but this was tried for some months without success; he was therefore transferred to a Military Hospital. On examination on May 12, 1943, his lumbar spine was found to be flattened and all movements at this level were limited, especially flexion. There was severe wasting of the right quadriceps and hamstring muscles, moderate wasting of the muscles supplied by the lateral popli-

teal nerve and minimal wasting of the calf muscles. The maximum circumference of the right thigh was 2¾ inches less than the left and the maximum circumference of the right calf ¼ in. less than the left. There was weakness of the extensors of the right leg, ankle and toes to a degree corresponding to the wasting. Flexion of the ankle and toes was not detectably weak. Passive straight leg raising on the right side only reached an angle of 30 degrees off the bed before giving rise to pain, but 75 degrees was reached on the left side. The right knee-jerk was absent but the left normal; the ankle-jerks were equal and the plantar responses flexor. The only point of tenderness was in the upper outer quadrant of the right buttock. There was no loss of postural sensibility on the right side but there was minimal loss of pain and touch sensibility over the right 3rd, 4th and 5th lumbar dermatomes. The clinical diagnosis was right-sided sciatica due to prolapsed intervertebral disc and extensive damage to the 3rd, 4th and 5th lumbar roots due to the effects of lipiodol and operation, and exacerbated by long hospitalization. On May 20, 1943, electromyographic recordings were made from the muscles of the right lower extremity. Despite the considerable wasting of the right quadriceps, only a few fibrillation action potentials were recorded from most of the positions of the needle-point in the muscles. Voluntary effort was accompanied by an outburst of motor unit activity sufficient to obliterate at least half of the time-base tracing on the oscilloscope. Fibrillation action potentials were also recorded from the muscles supplied by the anterior tibial nerve but they were few in number and were not observed at all positions of the electrode in the muscle. The motor unity activity was reduced to obliteration of three-quarters of the time-base tracing on the oscilloscope. No fibrillation action potentials were obtained from the calf, hamstring, peroneal or gluteus maximus muscles. Motor unit activity was reduced, however, but far less than in the quadriceps or muscles supplied by the anterior tibial nerve. From the gluteus medius and minimus muscles and to a lesser degree from the calf, peroneal and anterior tibial group of muscles, spontaneous rhythmic motor unit action potentials were recorded in a few positions of the needle point. Voluntary movement was without influence on these action potentials. It was noted in this case, and has been noted in others, that such action potentials are most common in positions of maximum tenderness in muscles but are not confined to them. In addition to the rhythmic action potentials, the insertion of the electrode into these areas provoked a more intense and more prolonged outburst of motor unit action potentials than in normal muscle.

In view of these findings, which suggested that the lesion was compounded of a minimum of denervation and a maximum of reversible ischæmic block, it was predicted that if the cause of the patient's pain was removed, the prognosis as regards recovery of function would be good. On July 31, 1943, a further lumbar laminectomy was done and a prolapsed nucleus pulposus at the L.4-5 level on the right side was removed. Following the operation he lost his pain, and his condition steadily improved; the thigh muscles increased in bulk rapidly and within three months of the operation he was back on light duty in the Army. He was seen again on May 19, 1944. He had been back on duty as a clerk and was able to fulfil his duties satisfactorily. There was now only slight wasting of the right thigh and calf; dorsiflexion of the right ankle was still weak, however. The knee-jerk was still absent on the right but the ankle-jerks were brisk and equal. This case illustrates the value of electromyography in diagnosis and prognosis.

Case 2. This case, also due to a prolapsed intervertebral disc, is in striking contrast to the previous one. Spr. P. B., aged 38, was admitted to a Military Hospital on November 27, 1942. He gave the following history. Two and a half

but he had remained free from pain and was able to carry out his military duties satisfactorily. Electromyographic recordings were very similar to those obtained before operation except for occasional small highly polyphasic motor unit action potentials which were recorded from the extensor hallucis longus, tibialis anterior and extensor digitorum longus and brevis muscles.

In Case 1, in contrast to Case 2, there was evidence of severe denervation and minimal reversible ischæmic block from the electromyographic point of view, and this was borne out by the clinical course of the case.

In more typical cases of sciatica occasional motor unit action potentials which repeat rhythmically, despite apparently complete relaxation, and which are unaffected in rate by voluntary movement appear in muscles supplied by the affected roots. The insertion of the electrode into such muscles also causes an abnormally vigorous and prolonged outburst of motor unit action potentials. Fibrillation action potentials are rarely encountered.

Case of sciatica due to a fractured sacrum.—Pte. R. L. I., aged 27, was admitted to a Military Hospital on March 24, 1943. He gave the following history. On February 22, 1943, he was working beneath a lorry which was struck in the rear; this caused the differential casing of the stationary lorry to move forward and strike him over the sacrum. He immediately had red-hot shooting pains down the back of both thighs and felt numb in both legs, front and back. For four days following the accident he could not pass his water and had to be catheterized; in addition his bowels were not open for a similar period and his legs remained numb. After this the numbness began to pass off and his urinary and bowel functions returned, but the pain down the back of his thighs persisted. He was treated by rest in bed and radiant heat, but the pain only very slowly grew less. It was aggravated by sitting, standing or coughing. He did not notice any weakness of his legs after the accident, for the pain was so severe when he moved them that he never tried them out fully. He was transferred to a Military Hospital one month after his injury, when he was improving. On examination he was ambulatory, and stated that he was now getting better slowly. His gait was normal. His lumbar spine was somewhat flat but movements at this level were full. There was no obvious wasting of the muscles of either leg, the left calf being ¼ in. less in maximum circumference than the right, and movements at all joints full. There was severe weakness of the calf muscles and intrinsic muscles of the feet, greater on the right side than the left, and clawing of the toes, again most pronounced on the right side. The knee-jerks were present and equal but both ankle-jerks were absent, as were the anal and bulbo-cavernous reflexes. The plantar responses were flexor. He was tender over the sacrum and along the course of both sciatic nerves in the buttocks and along the course of the right sciatic nerve only down the thigh and calf. Passive straight leg raising was up to 45 degrees on the right and 50 degrees on the left before the onset of pain. There was severe sensory impairment over the skin supplied by the second sacral dermatome and, to a lesser extent, the first sacral dermatome on the left side. On the right side sensory changes were minimal but of similar distribution. X-rays showed a fracture of the sacrum with a small degree of displacement, chiefly between the first and second pieces, and a bilateral fracture of the transverse processes of the fifth lumbar vertebra. The clinical diagnosis was

months before admission, when straightening up after helping to lift a heavy weight, he had a sudden severe stabbing pain in the right sacro-illiac region. It eased off after twenty minutes but recurred again when he tried to lift a large crate; this time, however, the pain did not improve, and the next day he noticed on awakening that it had extended down his leg to the middle of the back of his thigh. The pain was so severe when he moved around that he had to go to bed for nine days, during which time the pain in his back got entirely better but that in his leg persisted in some degree. At the end of this time it was considered that he had improved sufficiently to be allowed out of bed. However, the following day, when standing up, he placed the whole of his weight on his right leg and a severe pain shot down into the calf muscles and over the outer aspect of his leg which at once gave way beneath him. From that time the leg remained weak with persistent foot-drop, and the skin over the outer side of the calf was insensitive. The pain gradually grew less but was constantly present and made worse by standing. It was confined to the inner aspect of the right calf and was no longer made worse by coughing or sneezing. The condition remained stationary until his admission to hospital. On examination there were only 2 cm. diminution in the maximum circumference of his right calf and there was no wasting of his right thigh. There was weakness of all muscles of sciatic distribution, but the muscles supplied by the lateral popliteal nerve were most severely affected. The tibialis anterior and extensor longus digitorum could just move the joints against gravity, but the extensor hallucis longus and extensor digitorum brevis muscles were not felt to contract. The peroneal muscles were only moderately weak. The knee and ankle jerks were present and equal and the plantar responses flexor. There was complete sensory loss over the right 5th lumbar segment. Electromyographic recordings on December 10, 1942, showed many fibrillation action potentials in all positions of the needle-point in the muscles supplied by the anterior tibial nerve. In the other muscles of sciatic distribution there were only a few fibrillation action potentials and vigorous motor unit activity. The number of motor unit action potentials which could be obtained from the muscles supplied by the anterior tibial nerve was much reduced (2 or 3 per needling), and particularly few were obtained on insertion of the needle electrode in the extensor hallucis longus and extensor digitorum brevis muscles. These findings suggested a severe lesion of the 5th lumbar nerve on the right side and it was predicted that the chances of recovery of function in the severely affected muscles, particularly the extensor hallucis longus, were poor. On the other hand, in the remaining muscles the prognosis was thought to be good if the cause of the lesion did not recur or was removed. The patient was operated on on December 22, 1942, and a prolapsed intervertebral disc at the L.5-S.1 level on the right side was removed. Within three weeks of the operation there had been some increase in power as the result of maximum voluntary effort in the tibialis anterior and extensor digitorum longus, and a definite improvement in the peroneal muscles, hamstrings and muscles supplied by the medial popliteal nerve. The extensor hallucis longus and extensor digitorum brevis muscles were still paralysed, however. He was now quite free from pain but the area of sensory loss remained as before. Three months after operation, there was some further improvement in the power of the right tibialis anterior and extensor digitorum longus muscles, and the sensory loss was now incomplete; no other changes were observed. Electromyographic recordings paralleled the clinical findings. There was an increase in the number of repetitive motor unit action potentials recorded from all the affected muscles. He was returned to duty in a low medical category with a "toe-raising spring." On May 24, 1944, he was seen again. Clinically there had been no further improvement,

provoked by the insertion of the needle electrode are more in number and more prolonged than in normal muscles. The pain in the nodules which give rise to spontaneous motor unit activity, described by Elliot, is abolished by local infiltration of Procaine, and the suggestion has been put forward that the spasm itself is the source of the pain. Our findings, however, suggest that the pain in sciatica and analogous conditions may be the result of changes in sensory nerves which parallel those occurring in motor nerves.

Lesions, usually termed "irritative," of the peripheral neuraxon which lead to slow degenerative changes usually terminating in Wallerian degeneration, are most commonly the seat of an increased or abnormal distribution of pressure (i.e. sciatica due to prolapsed intervertebral disc, cervical rib, &c.). An increase of pressure in itself is unlikely to be the cause of the pathological changes, for isolated nerves can conduct normally under enormous hydrostatic pressure (Grundfest, 1936). It is probable that the pressure changes result in ischæmia which in turn initiates the degenerative changes. Ischæmic changes most commonly affect the motor before the sensory components of mixed nerves (Denny-Brown and Brenner, 1944*a*), and may give rise to local lesions of peripheral nerves which can be demonstrated histologically. As the result of such lesions it would appear that, eventually, changes take place at the nerve terminals which lower their threshold to stimulation. Masland and Wigton (1940) have shown that the "motor unit" action potentials induced by prostigmin are conducted centrally along the motor nerve, and it seems to us not unreasonable to suppose that the same thing happens in sensory nerves, thus accounting for the pain in "irritative" lesions such as sciatica and "radiculitis." If this hypothesis is accepted, an explanaton has been found for continuous pain in sciatica and allied conditions, although the factors concerned in the reduction of nerve terminal thresholds still remain obscure.

This elaboration of our findings would serve to explain the beneficial results of a number of therapeutical methods, for any process which serves to reduce the number of stimuli ascending to the central nervous system, either by blocking at the trunk level *or* at the level of the nerve terminals, would be effective. That the pain in nodules in sciatica is due to localized spasm of muscle is unlikely in view of the absence of pain in motor neuron disease, and the fact that all nodules are not painful and some painful areas are not clinically or electromyographically the seat of spasm.

a cauda equina lesion involving the 1st and 2nd sacral nerves on both sides resulting from a fractured sacrum. A sweating test showed a relative hyperhydrosis over the area of sensory loss on the left side (S.1 and S.2). It was clear that the patient was recovering, but there was some doubt as to the nature of the patient's motor disability. The wasting of the right calf was not appreciable and the muscle "tone" was reported to be "good." In fact, the left calf was slightly smaller than the right and yet it was by far the stronger. Electromyographic recordings from the muscles of both lower extremities were made on July 22, 1943. Fibrillation action potentials were recorded from all the muscles supplied by the first and second sacral nerves in all positions of the needle-point. There was also motor unit activity in all the affected muscles on insertion of the needle electrode, but repetitive action potentials in response to voluntary effort were reduced in number. The motor unit activity was particularly reduced (1 or 2 action potentials per needling) in the right gastrocnemius muscle in which fibrillation activity was vigorous. The soleus muscle on the right side, however, was not so severely affected. In a few positions in the affected muscles only, repetitive motor unit action potentials unaffected by active movements were recorded and the outburst of action potentials on insertion of the electrode was greater in number than normal and lasted for periods up to two seconds.

The results of this investigation were indicative of a severe degree of damage to the first and second sacral nerves, and, in view of the position of the lesion, the prognosis was considered to be relatively poor as regards full return of functional activity. Thus in this case electromyography proved of definite diagnostic value. It is interesting that the wasting was so unobtrusive in this case, and it is tempting to speculate that the absence of damage to the autonomic fibres at this level (sweating test) may have been related to this fact.

The spontaneous repetitive motor unit action potentials described in the above quoted case are in no way different from those recorded from "fasciculating muscles," and Elliot (1944) has recently drawn attention to the fact that tender spots or nodules in muscles supplied by "irritated nerve roots" are the seat of an increased motor unit activity on insertion of the electrode and often give rise to a continuous repetitive discharge of motor unit action potentials. Thus from the electromyographic point of view there is a close parallel, as regards spontaneous repetitive motor unit activity, between the findings in "fasciculation" induced by prostigmin, certain cases of sciatica, peripheral nerve lesions where the denervation process is incomplete or slowly progressive and "motor neuron" disease. The fact that the action potentials are quite uninfluenced by movement or attempted movement of the affected muscles is in favour of a peripheral rather than a central origin of the exciting process, and indeed there is proof of a peripheral (myoneural junction) origin of the spontaneous repetitive motor unit action potentials observed in "motor neuron" disease and those occasioned by prostigmin. Furthermore, the action potentials

General Summary.

Normal Muscle:—

(1) No electrical activity can be recorded from a voluntary muscle which is completely relaxed.

(2) It is possible to relax the majority of voluntary muscles completely without difficulty.

(3) Motor unit action potentials recorded with concentric (co-axial) needle electrodes vary in amplitude from 100 microvolts to one millivolt, and in duration from 5 to 10 milliseconds. They appear in response to voluntary contraction, and at the moment of insertion of the needle electrode (mechanical stimulation) into the muscle.

(4) Concentric needle electrodes have marked directional properties. The normal useful recording range is limited to 1 to 2 cm.

(5) There is no simple relationship between the motor unit activity within a muscle and the degree of "muscle tone" determined by the resistance experienced when a limb is moved or displaced passively. The factors responsible for this discrepancy have been analysed.

Denervated Muscle:—

(6) Repetitive action potentials from fibrillating muscle fibres can be recorded from denervated voluntary muscles provided they are at approximately blood temperature.

(7) Fibrillation action potentials are of two types, those evoked by the insertion of the needle electrode, due to mechanical stimulation, and those which repeat rhythmically, due, presumably, to chemical stimulation. They take the form of rhythmic monophasic- or diphasic spikes 1 to 2 milliseconds in duration and up to 100 microvolts in amplitude repeating at variable rates from 2 to 10 per second.

(8) The time course of fibrillation activity in man is longer than in experimental animals. In limb musculature the onset is from the sixteenth to the eighteenth day, in the facial muscles from the twelfth to the fourteenth day and in the sacrospinalis muscles from the tenth to the twelfth day.

(9) Fibrillation action potentials have been obtained from muscles denervated for eighteen years, though the number and frequency of such action potentials is less than in recently denervated muscles.

(10) Fibrillation action potentials can be obtained from partially denervated muscles. In cases where the number of motor units separated from their nerve supplies is minimal the electrode will have to be moved freely through the muscle before action potentials are recorded. Spon-

taneous repetitive motor unit action potentials uninfluenced by voluntary effort, as well as fibrillation action potentials, are often obtained from muscles in cases of slowly progressive peripheral nerve interruption.

(11) In certain cases where the lesion is presumed to be the result of axonal interruption, fibrillation action potentials cannot be recorded. Such findings are explained on the assumption that (*a*) the disease process may involve the muscle fibres; (*b*) the denervated muscle fibres may have undergone morphological changes; (*c*) the nerves to the muscles in question may not have undergone axonal interruption, but be in a condition of reversible ischæmic block.

(12) The number and frequency of the fibrillation action potentials recorded from denervated voluntary muscle may be increased by raising the temperature of the circulating blood or warming the muscles under examination. On the contrary, a low temperature decreases the activity.

(13) The number and frequency of the fibrillation action potentials recorded from denervated voluntary muscle increases following the administration of prostigmin.

(14) There is no apparent relationship between the number and frequency of the fibrillation action potentials recorded and either the rapidity or the degree of muscle atrophy.

(15) Denervated muscles which have received adequate physiotherapy as judged by clinical examination, fibrillate vigorously, whereas denervated muscles which have not been treated fibrillate feebly and indeed, on occasions, no *spontaneous* action potentials can be recorded before warming the limb.

(16) In cases of reversible ischæmic block (i.e. Bell's palsy), motor unit action potentials can always be obtained on insertion of the needle electrode and it is usual to find a few repetitive motor unit action potentials which may or may not be under voluntary control.

(17) Fibrillation action potentials are absent or few in number and may be confined to discrete portions of the affected muscles in cases of reversible ischæmic nerve block.

Re-innervated Muscle:—

(18) A decrease in the number of fibrillation action potentials is recorded before the return of motor unit activity.

(19) At a variable interval after the decrease of fibrillation activity motor unit action potentials are recorded in response to attempts to move the paralysed muscles. The motor unit action potentials first appear close to the position of entry of the nerve into the muscle and spread from

this area. As motor unit activity increases fibrillation activity decreases.

(20) When motor unit potentials first make their appearance they are small and often difficult to distinguish from fibrillation action potentials, especially in muscles which are capable of delicate movements such as those of the face.

(21) The range of amplitude and the duration of motor unit action potentials from re-innervated muscle are greater than in corresponding normal muscles.

(22) There is a variable interval between the appearance of motor unit action potentials and the commencement of detectable functional recovery. This depends to some extent on the particular muscles involved.

(23) Small highly polyphasic motor unit action potentials are usually obtained from re-innervated muscle and their detection is of value from a diagnostic point of view. They are most numerous in the earliest stages of re-innervation, but may be obtained for over eighteen months after functional recovery.

(24) When motor unit action potentials first appear they cannot be sustained by voluntary effort.

(25) Experiments are described which suggest that regenerated motor units are composed of scattered muscle fibres. The scatter is least obvious in lesions of nerves in continuity.

(26) Evidence is brought forward which suggests that prostigmin facilitates neuromuscular transmission in the early stages of re-innervation.

Miscellaneous:—

(27) Case records illustrating the results of electromyographic investigations in the following specific neurological affections have been given. (1) Facial nerve paralysis; (2) intrinsic laryngeal muscle paralysis; (3) spinal cord injuries and diseases; (4) sciatica.

(28) In the early stages of "motor neuron" disease, the electromyographic picture of repetitive motor unit action potentials uninfluenced by voluntary contraction differs only in degree from that induced by prostigmin in normal muscle. In both cases the action potentials have been proved to originate at the myoneural junction.

(29) Repetitive motor unit action potentials of a similar type, though in minimal numbers, are seen in slowly progressive peripheral nerve lesions, the result of ischæmia. They also appear in so-called "rheumatic nodules." In the latter the pain and spasm are abolished by infiltration of a local anæsthetic.

(30) As the result of these observations it seems not improbable that there is a stage in the course of degeneration of a peripheral motor neuron

in which the threshold at the myoneural junction becomes greatly decreased so that spontaneous contractions occur.

(31) It is suggested that the pain in sciatica is due to a similar process affecting the sensory nerves and their endings. If this explanation is true it would explain the partial success of the large number of sciatica remedies, for any procedure aimed at reducing the number of peripheral stimuli reaching the cord, if successful, would be effective in reducing pain.

ACKNOWLEDGMENTS.

The expenses of this investigation were defrayed by a grant to one of us (G. W.) by the Medical Research Council, which is gratefully acknowledged. B. F. was in receipt of a personal grant from the Carnegie Research Fund, and R. E. P. from the Nuffield Fluid Research Fund, these are also gratefully acknowledged.

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LEGENDS TO ILLUSTRATIONS.

PLATE VII.

FIG. 1.—Motor unit action potentials evoked by the insertion of the electrode into a normal brachio-radialis muscle.

FIG. 2.—Record from a normal brachio-radialis muscle when completely relaxed.

PLATE VII.

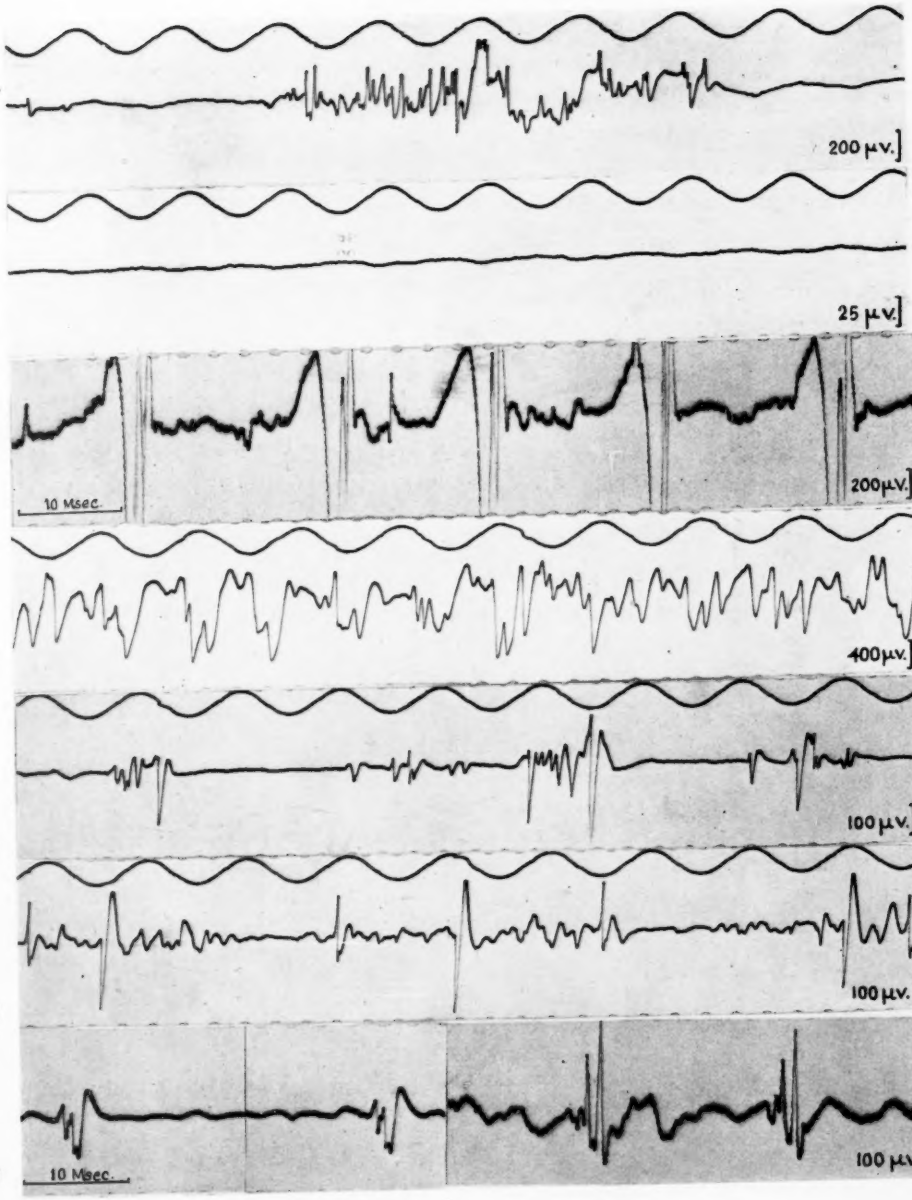

FIG. 1

FIG. 2

FIG. 3

FIG. 4

FIG. 5

FIG. 6

FIG. 7

To illustrate article by G. Weddell, B. Feinstein and R. E. Pattle.

PLATE VIII.

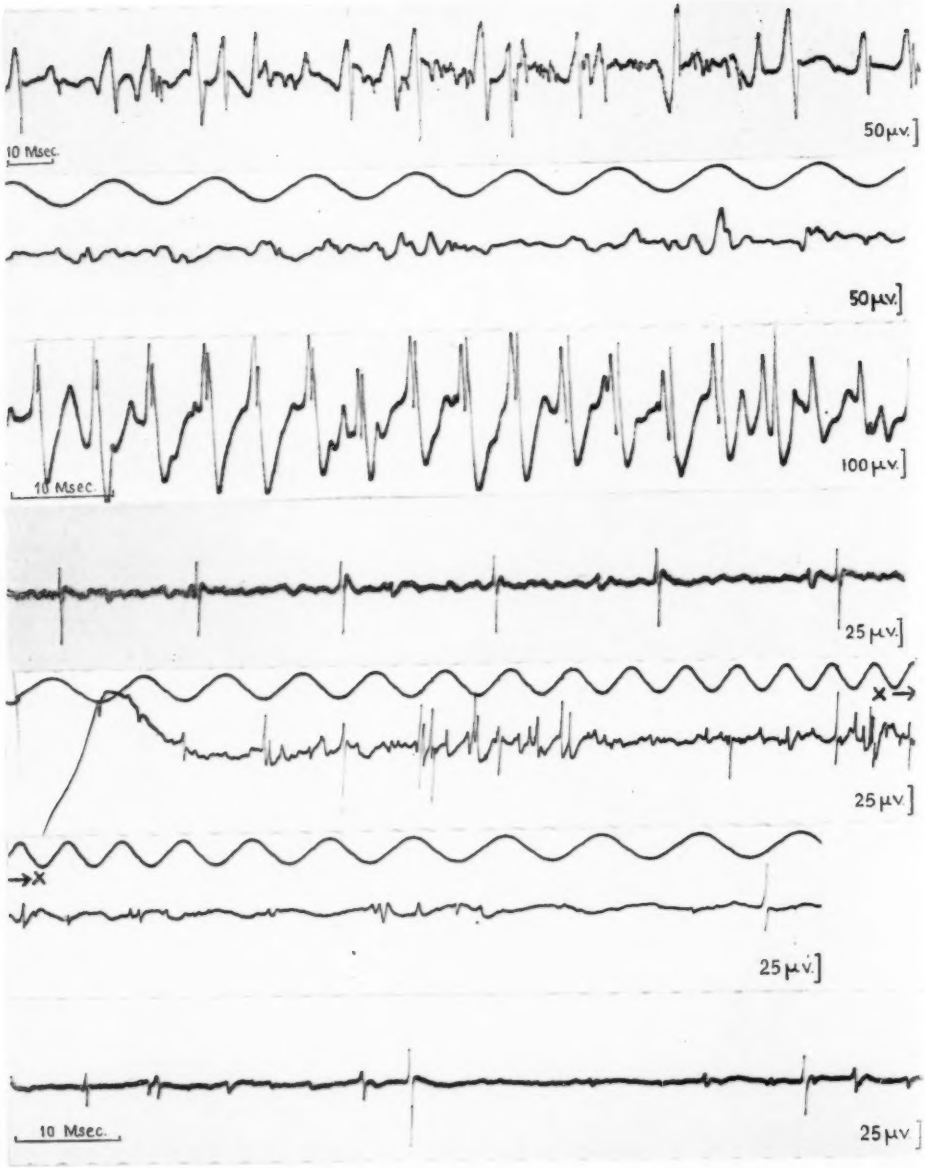

FIG. 1

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To illustrate article by G. Weddell, B. Feinstein and R. E. Pattle.

PLATE IX.

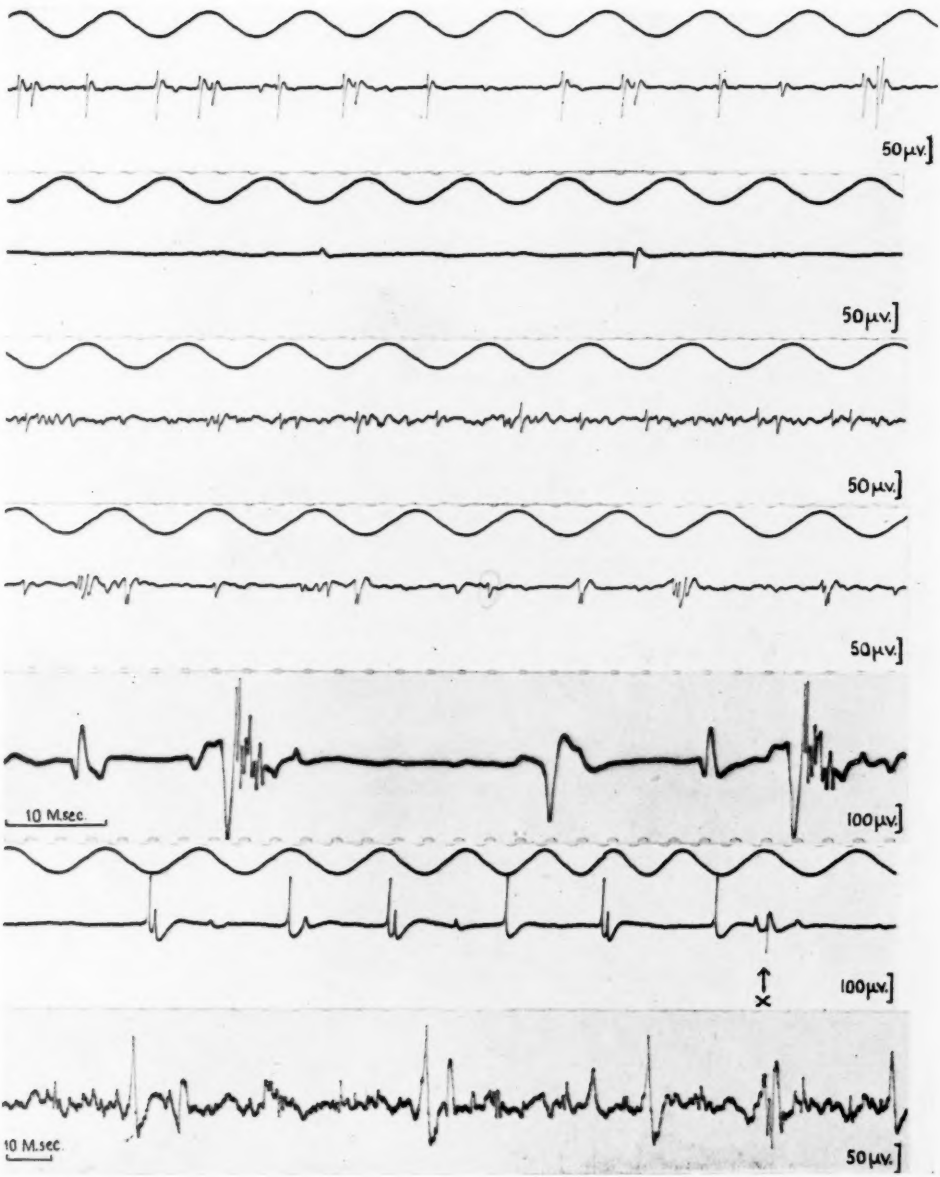

FIG. 1

FIG. 2

FIG. 3

FIG. 4

FIG. 5

FIG. 6

FIG. 7

To illustrate article by G. Weddell, B. Feinstein and R. E. Pattle.

FIG. 3.—A large polyphasic motor unit action potential from a normal brachio-radialis muscle repeating 50 times per sec.

FIG. 4.—Record from a normal brachio-radialis muscle during a maximal isometric contraction.

FIG. 5.—Monophasic motor unit action potentials from a normal brachio-radialis muscle (minimal voluntary contraction).

FIG. 6.—Diphasic motor unit action potentials from a normal brachio-radialis muscle (minimal voluntary contraction).

FIG. 7.—Triphasic motor unit action potentials from a normal brachio-radialis muscle (minimal voluntary contraction).

PLATE VIII.

FIG. 1.—Record from normal facial musculature. Compare with Plate III, figs. 5, 6 and 7, and Plate V, fig. 7.

FIG. 2.—Record from a paralysed flexor carpi ulnaris muscle (ulnar nerve blocked with local anæsthetic) during a maximal isometric contraction of the wrist flexor muscles. The point of the electrode was against the sheath of the muscle opposing the median flexors.

FIG. 3.—High-frequency motor unit action potentials evoked by the insertion of the electrode into the right brachio-radialis muscle in a case of myotonia congenita.

FIG. 4.—Action potentials lasting five seconds, and resembling those from fibrillating muscles, which followed twenty seconds after the insertion of the electrode into the brachio-radialis muscle in a case of myotonia congenita.

FIG. 5.—Fibrillation action potentials evoked by the insertion of the electrode into a denervated abductor minimi digiti muscle. The tracing is continued in fig. 6.

FIG. 6.—Two seconds have elapsed between the points X in figs. 5 and 6.

FIG. 7.—Fibrillation action potentials from a denervated brachio-radialis muscle which had received vigorous physiotherapeutical treatment.

PLATE IX.

FIG. 1.—Fibrillation action potentials from a denervated sacrospinalis muscle.

FIG. 2.—Record from a denervated extensor carpi radialis longus muscle.

FIG. 3.—Record from the same muscle twenty minutes after the administration of 2·5 mg. of prostigmin subcutaneously.

FIG. 4.—Motor unit action potentials from recently re-innervated facial musculature. These are sometimes difficult to distinguish from fibrillation action potentials.

FIG. 5.—A highly polyphasic motor unit action potential recorded from a partially re-innervated extensor carpi radialis longus muscle. (Minimal voluntary contraction.)

FIG. 6.—Record from a brachio-radialis muscle immediately following insertion of the electrode in a case of "motor neuron" disease. The motor unit action potentials are of high frequency and were unrelated to movement. At X is a fibrillation action potential which repeated rhythmically about 5 times a sec.

FIG. 7.—Record from laryngeal musculature; inter-arytenoids. In this case the motor unit activity was less than normal. (Compare Plate III, figs. 5, 6 and 7, and Plate IV, fig. 1.)

FAMILIAL TUBEROSE SCLEROSIS WITH CALCIFICATION. REPORT OF TWO CASES.

BY SQUADRON LEADER JOHN APLEY, R.A.F.V.R.

DESPITE the fact that the diagnosis is being made with increasing frequency, tuberose sclerosis, the "potato-like" sclerosis of the brain, remains a comparative rarity. In its classical form many of the systems of the body may be involved and it is characterized by: (1) epileptiform fits, (2) mental deficiency, (3) skin lesions and (4) tumours of the eye, in addition to sclerosis of the cerebrum.

In a moderate proportion of the recorded cases calcification of the sclerosed areas in the brain is demonstrable by X-ray. Such calcification was present in both the father and child described in this paper, although in an X-ray of the child's skull taken two years previously it had been absent.

CASE REPORTS.

Case 1. The father.—The patient was aged 36 when first seen, two years ago. An eruption had been present on his face since childhood, but the diagnosis of adenoma sebaceum had not been made until he was examined in the R.A.F. As a result, further investigation was obviously suggested. Until this time the patient had denied the occurrence of other disturbances, but he now admitted to suffering from fits, and the full history was unfolded.

Several events of medical importance had taken place at approximately the same time, when he was 6 years of age. A large "mole," which for some years, possibly since birth, had been present on the back of his neck, was removed at that time. Almost immediately afterwards many warts appeared on his trunk and limbs, and have persisted since. At about the same time the eruption on his face appeared, and for the first time he had a fit.

With this first fit he was seriously ill. For the next few years he suffered from what were called "fainting attacks," but these have gradually changed in character, and are now described as "giddy turns." They may come on at any time and in any position: he feels giddy and confused, he cannot obey orders, he may drop articles he is holding, and he does not fully realize what he is doing. The attacks vary in severity; frequently he does not lose consciousness, and sometimes lying down at the onset enables him to get up in a few minutes feeling quite well. At other times he merely feels slightly giddy for about half an hour. Rarely, he falls over during an attack; on one occasion, in a particularly severe attack during which he must have been unconscious for several minutes, he seems to have walked into a tree. As a rule, he feels listless after an attack, but is not sleepy, nor is there any headache. The attacks occur at intervals of one or many weeks; phenobarbitone and epanutin have no apparent effect on their frequency or severity. He feels certain that he is more prone to attacks if he is shouted at or bullied!

He feels diffident in his attitude to others because of his "turns," but does not consider that they affect him in any other way. Very occasionally he suffers from a mild vertical headache, which has no relation to the giddy turns.

There is no history of illness in the past, other than that already recorded. He is the fourth of five children (2 brothers and 2 sisters) all of whom are stated to be alive and in good health. The father died of heart disease. There is no history of any relevant condition in the remainder of his family, other than that his mother's sister (a twin) suffered from fits in childhood.

He affirms that at school (a small public school) he was rather backward, and left at the age of 15. He then failed in the general knowledge test for a bank career, and was set up in business. For many years since he has conducted his own business, and with success. During the short time in which he served in the R.A.F. he carried out police duties satisfactorily, not disclosing the history of fits.

On examination.—He appears of average intelligence, though rather slow of speech, and with a normal approach to the problems of his private life and of the Service.

He is of good general physique and well nourished. His head appears to be rather large, and his size in hats in 7⅞.

On the face the typical "butterfly" distribution of adenoma sebaceum was seen, originally extending slightly on to the chin and nose. Now, after two years, the nose has become completely involved. The eruption consists of a conglomeration of pinkish-yellow raised spots, superficially resembling acne vulgaris. Many piliform warts are also present, mainly in the flexures of the arms, but also sparsely distributed elsewhere. On section these showed the characteristic appearance of benign papillomata with slight hyperkeratosis.

Rhonchi were present in both lungs on some occasions, and an X-ray of the chest confirmed the diagnosis of mild bronchitis. No abnormalities were found in the cardiovascular system or abdomen. In the central nervous system no localizing signs were discovered, and an electro-encephalogram was normal.

X-ray of the skull showed many widely scattered opaque areas, whose general appearance and density were suggestive of calcification. By stereoscopic films they appear to be located within the skull (fig. 1).

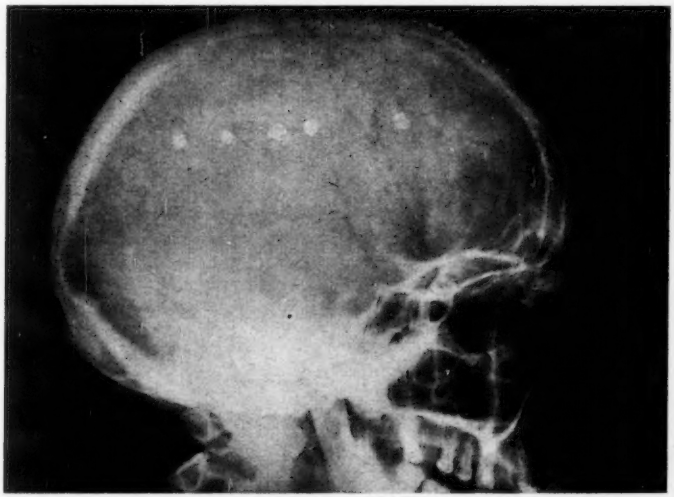

FIG. 1.

Flight-Lieutenant J. R. Acfield, Ophthalmic Specialist in the R.A.F., reported that vision in both eyes was normal. On examination of the fundus of the left eye a grey mass was seen at the nasal edge of the disc. It was about one-fifth the size of the optic disc, and a small artery passed through its upper portion. Two years ago it presented only a slightly "mulberry" appearance, but this has now become clearly evident.

Various pathological investigations were carried out, all of which proved negative. These included examination of the C.S.F., W.R., Lange curve, blood-sugar curve, &c. The phalanges and other bones of the limbs showed no abnormality on X-ray.

Case 2. The child.—The family history on the father's side has already been discussed. The mother was stated to be hysterical, uninterested in the child, and withdrawn into herself, but no other relevant facts were elicited. There was no history of miscarriages. The boy was an only child. Parturition had not been associated with any untoward difficulty, and there was no history of trauma since birth.

The father described the boy as having been a "crying type of infant," who had been backward in talking and in whom eruption of the teeth had been slightly retarded.

Fits had commenced at the age of 15 months, and are described as of two types. During the milder attacks he may cry out "Nobody's going to hurt me," and suddenly look blank, but does not fall. If a severe attack occurs during the day he falls, and may remain unconscious for several minutes. Involuntary micturition may then occur, his hands and face are said to twitch, he appears to be struggling to make swallowing movements, and he may bite his tongue. During one unusually severe attack at the age of 3 he remained unconscious for a quarter of an hour, and could not speak for several hours afterwards. The severe attacks occur almost invariably during his sleep. In the last few years they have become increasingly frequent, and he may have as many as ten in a night, often with a week or so between these bouts. Phenobarbitone appears to have no effect in mitigating the severity or reducing the frequency of the attacks, but epanutin apparently increases the length of time between attacks.

Definite and increasing evidence of mental and moral aberration was found. When he was first examined, two years ago, his attention could not be held for long, and he was restless and fidgety: concentration was poor though memory was good, and he was said to be mischievous. Now, at the age of 5¾ years, he cannot write but can read a few simple words. He has become violent and destructive, tells lies as facilely as the truth, steals without hesitation, and masturbates frequently. He likes to play with other children, but they, apparently, do not share this enthusiasm!

On examination.—A well-built child, of good average height and development. He holds his rather small head in a manner characteristic of the mentally deficient. All the teeth are present. Clinical examination of the heart, lungs, abdomen and central nervous system (including the optic fundi) is negative.

Two years ago the skin appeared completely clear, but now there are several small warts on the anterior aspect of the right knee, and one on the chin. Immediately above the right naso-labial fold a small spot, resembling those of adenoma sebaceum, has recently appeared.

An attempt was made to carry out electro-encephalography, but he was unable to sit still for a sufficient length of time.

X-ray films of lungs and bones taken two years ago appeared normal. The skull X-ray taken at that time was also normal, but in the X-ray films of the skull taken recently several small opacities have become visible (fig. 2).

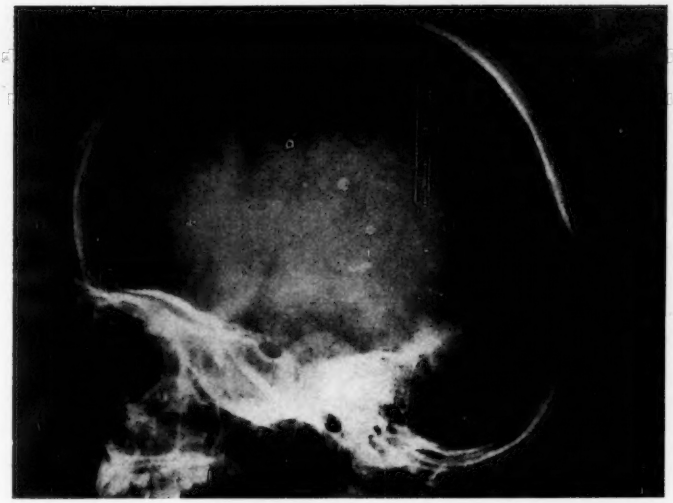

FIG. 2.

DISCUSSION.

Ætiology.—The ætiology of tuberose sclerosis is unknown, but it is considered to belong to the group of ectodermal dysplasias (congenital ectodermoses) (Yakovlev and Guthrie, 1931). Frequently, but by no means invariably, there is evidence of an heredo-familial disorder. Thus, in one family, six individuals were affected in three generations (Kirpiznik, quoted by Quill and Marting, 1941). On the other hand, Ross and Dickerson (1943) state that of 25 cases they studied not one was the child of a parent with tuberose sclerosis, though one parent had a convulsive disorder. The existence of "formes frustes" of the disease, in which only one or few of the characteristic features may be present, must be appreciated in any investigation into the heredity of the condition.

Skin lesions.—The characteristic lesion is facial adenoma sebaceum, a benign hyperplasia of the sebaceous glands. There are several variations in type, but Pringle's original description (Pringle, 1890) still merits quotation: "The eruption, which the patient says is painful in cold weather, consists of indolent, firm, whitish or yellowish, sago-grain-like solid papules or little tumours embedded in the skin at different levels, or projecting from it, and varying in size from that of a pin-point

idiocy. Since 1932, when their paper appeared, many considerably milder forms have been described, and their undue proportion of high-grade defectives is presumed to be inherent in the method of selection of cases from institutions.

Tumours of the eye.—The occurrence of tumours of the eye in tuberose sclerosis was first recorded by J. van der Hoeve in 1920 (van der Hoeve, 1932), who termed them "phakomas," from the Greek "phakos," a mother-spot. Messinger and Clarke (1937) collected 24 cases from the literature, and, in contrast with van der Hoeve, who had demonstrated them in every one of his cases, found them in only a small proportion. The typical finding is of an approximately circular white or grey area in the retina, the size of which is usually about half that of the disc.

X-ray changes.—The most striking feature is the occurrence of multiple opacities scattered throughout the skull, for which the term "brain stones" is particularly apt (Yakovlev and Corwin, 1939). Their appearance was first described by Daalsgard-Nielsen (cited by Heublein *et al.*, 1940), who thought them extremely rare. Ross and Dickerson (1943), on the other hand, found that in only 5 of 25 cases were areas of calcification absent in the skull X-rays.

Yakovlev and Corwin (1939) concluded that all tuberose sclerosis cases with cerebral opacities were past puberty; the one younger patient in their series, a girl of 7, showed none. The child described in this paper, at the age of 5¾ years, appears to be the youngest in whom these opacities have been demonstrated. Lichstein and Solis-Cohen (1943) have recorded the hitherto unique finding of opacities in a father and his child, also adult; in neither of these cases, however, was adenoma sebaceum present, and in only one did fits occur.

Skeletal changes may form part of the syndrome, but according to Hall (1940) they are rare. The least uncommon are osteoporotic and cystic changes in the distal bones of the extremities.

Electro-encephalography.—Kemm Good and Garb (1943) have reviewed the application of electro-encephalography to tuberose sclerosis. They emphasize that the tracings obtained at different times from one individual may vary from a "border-line normal record" to one "suggestive of a convulsive disorder." For this reason each patient should be examined on more than one occasion. Such a precaution was omitted in the investigation of Case 1, but in patients in whom the cerebral lesions are very slowly progressive, or stationary, no change in the electro-encephalogram would be anticipated.

to a small pea." The eruption appears superficially acneiform; its distribution on the face is in the shape of a butterfly, with the wings involving the naso-labial folds (where it makes its first appearance) and cheeks, and the body covering the bridge of the nose.

Other abnormalities of the skin are also encountered, of which the commonest are small, flattened fibromata. Clusters of pedunculated dermal tags may be seen, and occasionally *café-au-lait* patches or vitiligo.

Critchley and Earl (1932) affirm that when adenoma sebaceum is in the foreground neuro-psychiatric features may be inconspicuous and not progressive. This is borne out by a comparison of the dermatological and mental aberrations in the present two cases.

Ross and Dickerson (1943) claim that facial lesions almost always precede convulsions, but in these two cases this claim is not confirmed.

Epilepsy.—Epilepsy is said usually to become manifest in the first two years of life (Critchley and Earl, 1932). Ross and Dickerson (1943) state that there are frequently long periods of freedom from attacks, although in these intervals mental deterioration usually continues. In both these respects the father does not conform.

In the reported cases there is general agreement that *grand mal* or *petit mal* attacks may occur singly or together, and also that variations from the normal are surprisingly few in the examination of the central nervous system.

Mental deficiency.—In the progress of a case of tuberose sclerosis, as in other types of mental deficiency, the first abnormality noted is usually a developmental delay (Critchley and Earl, 1932). Talking, sitting up, walking, &c., are retarded, and by the third year mental deficiency is, as a rule, clearly demonstrable. "At about the time of the second dentition the patient begins to lose ground and show increasing dullness, disordered conduct, spitefulness, emotional outbursts and impairment of speech. In many such instances admission to an institution becomes necessary. The course is rapidly downhill after puberty." The child here recorded appears likely to fulfil this gloomy prognosis. The father, on the other hand, although his early history suggests some mental retardation, has shown no deterioration since puberty; in his mental powers, too, he has little in common with the typical case of fully developed tuberose sclerosis.

According to Critchley and Earl (1932) a fully developed case shows a combination of an intellectual defect proper with a primitive form of psychosis, the latter resembling catatonic schizophrenia. Of the 29 cases described by these authors all fell into the categories of imbecility or

CREATINE METABOLISM IN RELATION TO PITUITARY TUMOURS.

BY J. N. CUMINGS

(From the Biochemical Laboratory, National Hospital, Queen Square, London.)

SCHRIRE (1937) has described some experiments conducted in relation to pituitary disease with special reference to creatine metabolism. He found an increased and variable urinary excretion of creatine and creatinine in acromegaly together with an intolerance to creatine by mouth, and he discussed the possible reasons for his findings. Recently Tierney and Peters (1943) have given their results of creatine estimations in blood and urine after test doses of creatine by mouth in thyrotoxicosis. This paper describes the application of the test used by Tierney and Peters to patients with pituitary adenomata together with further observations confirming the work of Schrire, although differing from him in certain explanations of the mechanism of the creatinuria as a result of my findings.

MATERIAL.

The urines from 8 patients with a chromophobe adenoma and 16 with an acidophil adenoma of the pituitary have been examined for creatine and creatinine while on a meat- and fish-free diet. Examination of controls composed of non-pituitary cerebral lesions and of thyroid disease were also examined.

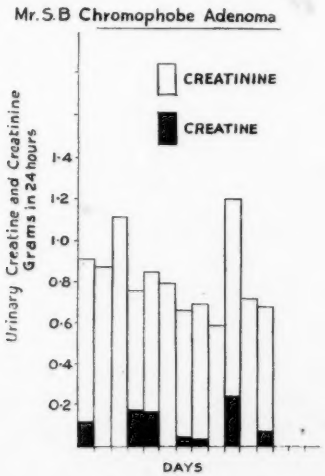

FIG. 1.

Kemm and Garb emphasize the importance of this method of investigation in the detection of "formes frustes" of the disease.

Summary.

(1) Tuberose sclerosis is described in a father and child.

(2) In the father all the claassical features of the syndrome were present, viz. (i) opacities in the skull, shown by X-ray; (ii) adenoma sebaceum; (iii) a phakoma; (iv) epileptiform fits; (v) mental retardation.

(3) At the age of 3½ years the child was mentally retarded and suffered from fits. Two years later his mental condition had deteriorated greatly, a few skin lesions had appeared, and opacities had become visible in the X-ray of his skull.

I wish to express my thanks to Squadron Leader E. J. Moynahan and to Flight Lieutenant J. R. Acfield for their help in Case 1.

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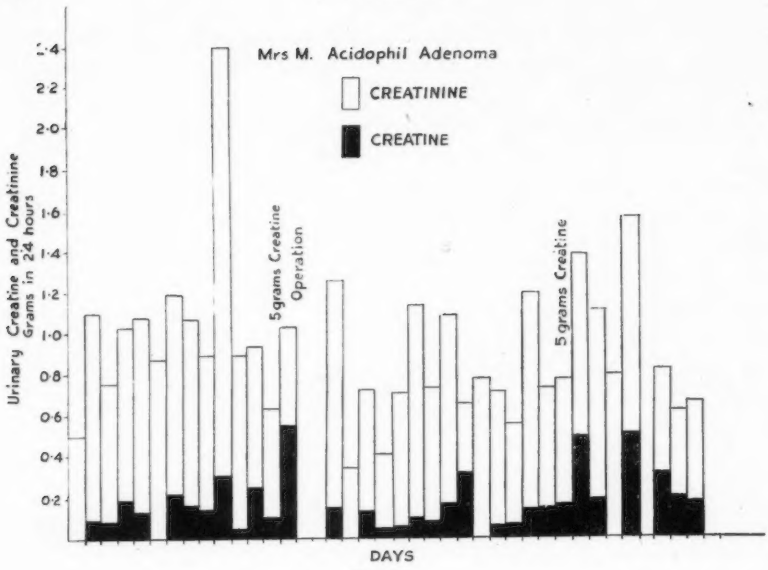
Mrs M. Acidophil Adenoma
CREATININE
CREATINE
Urinary Creatine and Creatinine Grams in 24 hours
5grams Creatine
Operation
5 grams Creatine
DAYS

FIG. 2.

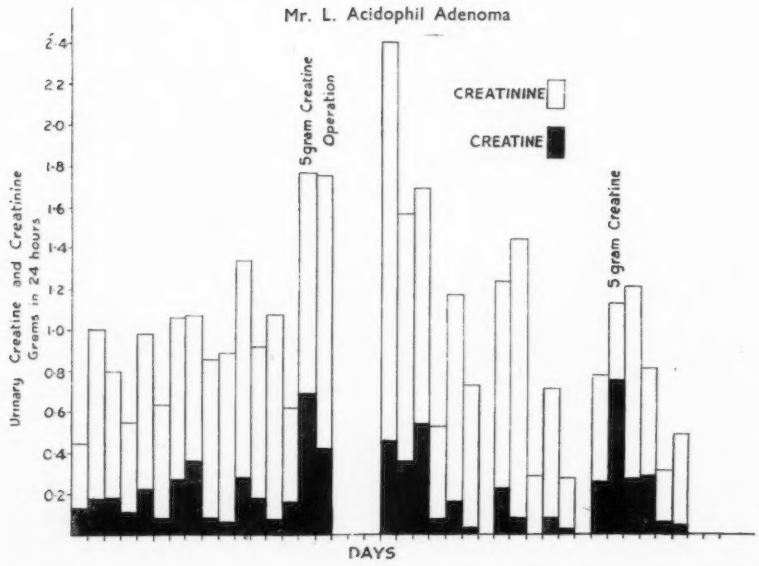
Mr. L. Acidophil Adenoma
CREATININE
CREATINE
Urinary Creatine and Creatinine Grams in 24 hours
5gram Creatine
Operation
5 gram Creatine
DAYS

FIG. 3.

Results.

All patients with a chromophobe adenoma have shown a normal or slightly raised excretion of creatinine and on some days small amounts of creatine. A typical example is shown in fig. 1. Operation for removal of the tumour caused no alteration in these findings.

In all the 16 cases of acromegaly the findings, examples of which are given in figs. 2 and 3, are in entire agreement with those of Schrire, namely a definite but variable amount of creatine, together with a raised quantity of urinary creatinine. Two of Schrire's cases were examined post-operatively and in one a return to normal rates of excretion occurred, but in the other no change took place. Operation was performed on 7 out of the above 16 cases and in none was there any real improvement in the urinary excretion figures of creatine, and clinically there was no real or permanent improvement. It appeared that the tumour had not been completely removed as the operation material invariably consisted of small fragments, and this was confirmed in one patient who was followed over a period of some five years. This woman at no time when examined showed any loss of urinary creatine and when autopsy was performed it was seen that portions of an acidophil adenoma were still present despite the operative interference.

It appears therefore that the urinary excretion of creatine under the conditions of a meat- and fish-free diet is sufficient to distinguish between the two types of pituitary adenoma in the absence of thyrotoxicosis and some muscular disorders.

Creatine Tolerance Test.

It seemed possible that the test used by Tierney and Peters might prove easier and more valuable as a method of diagnosis than the rather lengthy procedure of urinary examinations of the type used previously. 5 patients were examined, 3 with a chromophobe adenoma and 2 with an acidophil adenoma. The patients were on a meat- and fish-free diet, and the bladder was emptied after an eight-hours' fast and a sample of blood obtained. 1 grm. of creatine was given by mouth and samples of urine obtained, one, two and three hours later, blood being collected at the one and three-hour times. Creatine and creatinine were estimated in all the urine and blood samples by methods advocated by Tierney and Peters in their paper. The results are given in Tables I and II, and it is seen that the findings in the two types of adenoma are in striking contrast. The fasting blood creatinine, although within the normal range is higher in the patients with a chromophobe adenoma, rises after ingestion of

TABLE I.—CHROMOPHOBE ADENOMA.

Creatine Tolerance, i.e. 1 *grm. Creatine by Mouth.*

Name	*Time*	*Urine volume in c.c.*	*Urine creatinine total mgm.*	*Urine creatine total mgm.*	*Blood creatinine mgm.%*	*Blood creatine mgm.%*
Br. (Male) ..	Fasting				1·4	0·6
	1st hour	52	90	2·0	2·2	1·7
	2nd hour	66	82·5	10·0		
	3rd hour	50	93	6·95	2·19	2·61
Wr. (Male) ..	Fasting				1·22	0·4
	1st hour	32	58	1·3	1·95	0·47
	2nd hour	56	73	13·0		
	3rd hour	69	73	9·0	2·29	0·62
No. (Female)	Fasting				1·0	0·6
	1st hour	28·5	28·5	3·7	1·1	1·65
	2nd hour	88·5	66·4	35·4		
	3rd hour	16·5	13·2	5·28	1·4	0·7

TABLE II.—ACIDOPHIL ADENOMA.

Creatine Tolerance, i.e. 1 *grm. Creatine by Mouth.*

Name	*Time*	*Urine volume in c.c.*	*Urine creatinine total mgm.*	*Urine creatine total mgm.*	*Blood creatinine mgm.%*	*Blood creatine mgm.%*
Cl. (Female)	Fasting				0·35	1·16
	1st hour	41	45·1	61·5	0·75	1·25
	2nd hour	43	53·75	64·5		
	3rd hour	40	56·0	52·0	0·34	1·17
Mo. (Male) ..	Fasting				0·45	1·05
	1st hour	86	147·9	17·4	0·75	1·75
	2nd hour	42	88·2	12·6		
	3rd hour	48	67·2	76·8	0·7	1·4

creatine, and is still raised or even higher three hours later; whereas in acromegaly the fasting figure is lower, rises, but has fallen or is falling after three hours. The blood creatine findings are quite different. In acromegaly the fasting level is higher than normal, rises rapidly and tends to fall in three hours, whereas in a patient with a chromophobe adenoma the fasting figure is within normal limits, rises rapidly and tends to remain raised even after three hours. The urinary creatine is much higher in the acromegalic patient. The response to this test dose of creatine in a patient of either sex with a chromophobe adenoma is very similar to the response of a normal male subject as shown in the figures given by Tierney and Peters. The response of the acromegalic patient can be compared to the normal male response provided the initial base level is considerably raised, i.e. a raised fasting level of blood creatine. However the normal male excretes only minimal quantities of creatine in the urine, although the normal female excretes even more urinary creatine after ingestion of creatine than the acromegalic in spite of the former's normal and low fasting blood creatine, although this is probably due to

the fact that the normal female patients of Tierney and Peters were examined two hours after a creatine-free breakfast and not after a creatine-free diet of some days' duration as mine were. Neither type of tumour case shows responses similar to the hyperthyroid patient as in these much higher blood and urine creatine figures are obtained.

It would appear therefore that this method of examination does enable one to determine the nature of a pituitary tumour and it is also possible by this test to distinguish between pituitary and thyroid dysfunction.

Tierney and Peters have discussed the difficult problem of creatine metabolism and the part played by the kidney especially as regards reabsorption of creatine by the renal tubules when the serum concentration of creatine is less than 0·5 mgm.%. There does however seem to be some hormonal factor of the pituitary involved controlling creatine metabolism. Schrire suggested that one hormone factor elevated the creatine in the urine, possibly acting through the thyroid. This direction of action through the thyroid would be in agreement with the work of Tierney and Peters, but the method of elevation of urine would appear according to my results to be due to an elevation of the blood creatine and not due to any local action on the kidneys as suggested by Schrire. Neither Tierney and Peters nor I found urinary excretion of creatine with serum creatine figures of under approximately 0·5 mgm.% either in thyrotoxicosis or in either form of pituitary adenoma, so that it would appear that the renal tubules are not at fault. It appears that the acidophil cells however do control the concentration of the serum creatine, and that each increase in number and amount together. If this is so then the higher the blood creatine the greater the degree of severity of the lesion, but this can only be proved by the examination of larger numbers of cases.

SUMMARY.

The existence of abnormal urinary excretion of creatine in acromegalic patients has been confirmed.

A creatine tolerance test in which blood and urine creatine are estimated has been shown to be a useful method for the diagnosis of the types of pituitary adenoma.

My thanks are due to the members of the staff of the National Hospital for access to the patients under their care, and to the National Hospital Research Fund for an expenses grant.

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Notices of Recent Publications.

Mysticism in Modern Psychology. By Charles Carlé. Psycho-Sociological Press, New York. 1943. Pp. 47. Price One Dollar.

This series of short, but interesting, essays has as its sub-title the following, "Some critical remarks about magical trends in 'psychoanalysis' and 'psychodiagnostics'." The author maintains that we have to-day more secularized mysticism than in the "dark ages" of religious faith, that this modern mysticism is a pseudo-mysticism. "Anyone," he adds, "who really wants to fight quackery in psychology should have the courage to begin *intra muros.*"

Freud's theory of "drives" and his "cabalistic dream interpretations," and some developments of Rorschach's psychodiagnostics are cited as examples of mysticism, and cogent reference is made to the tendency of groups of disciples of these various cults to maintain a monopolistic and sacerdotal attitude in their exposition and employment.

Much of this exposition and employment is, he submits, pseudo-mystical and therefore "pre-scientific."

The author elaborates his thesis with specific examples and with citations from other writers, and ends with a plea for a non-mystical holistic concept of human nature.

The Vascular Abnormalities and Tumours of the Spinal Cord and its Membranes. By R. Wyburn-Mason. Henry Kimpton, London. 1943. Price 18s.

The author has collected and classified a large series of cases, and has provided a valuable pathological and clinical study of a category of spinal cord lesion not hitherto made the subject of any systematic generalization. The monograph does not lend itself readily to summary, but special reference may be made to the description of what is perhaps the commonest vascular anomaly of the spinal cord, namely, angioma racemosum venosum. This lesion has a characteristic mode of behaviour, reflected in its history and signs, and the method of kymography utilized by the author constitutes a valuable advance in diagnostic procedure when this lesion is in question.

We may endorse the words of Dr. Gordon Holmes in his foreword to the monograph, "of the clinical importance and practical value of this monograph I have no doubt, and I can only express the hope that it will receive the recognition to which the expenditure of much time, energy and exact observation entitles it."

A Textbook of Psychiatry for Students and Practitioners. By D. K. Henderson and R. D. Gillespie. Sixth Edition. Oxford University Press, London. 1944. Pp. 719. Price 25s.

The authors of this well-established and useful textbook have made considerable additions to it for this edition because they believe that remarkable progress has

occurred in psychiatry in recent years. No doubt they are right, but it may be questioned whether all of this progress is on assured ground. Prefrontal leucotomy may go the way of colonic resection, and the apparent triumphs of empiricism may turn out to be less fruitful than they seem now. It is difficult to follow the author's reasoning when they say that "the success of electric shock therapy in terminating such processes as constitutional depression, and of prefrontal leucotomy (cutting the frontal-thalamic fibres) in agitated impulsive states, reminds us that the brain, like the heart, is in many ways an electrical organ." The book has solid merits, warranting its popularity among students and practitioners; there is however a danger that some who might have been attracted to pursue a psychiatric career will be frightened away by the zestful statement, in the Preface, that "the complete psychiatrist of the future will have to be not only a doctor but a social anthropologist, a psychologist, at least an elementary statistician, perhaps something of a biochemist, and more than a little of a physicist." Although in the next sentence the budding psychiatrist is assured that he "need not be deterred but may rather think it 'blessed [*sic*] in that dawn to be alive' ", he may prefer a less exigent specialty.

An Introduction to Physical Methods of Treatment in Psychiatry. By W. SARGENT and E. SLATER. Livingstone, Edinburgh. 1944.

The spectator of psychiatric treatment gains the impression that its recent development has been mainly in the hands of the empiric and the doctrinaire enthusiasts whose methods win enough success to justify many of their more sober claims. The empiric, with his leucotomy, convulsions and hypoglycæmia, is convinced that "advance in the therapy of mental illness has now got safely under way." The doctrinaire, whatever his brand of psychoanalysis, urges with persistent logic that, on his premises, psychological ailments demand psychological remedies. The authors of this little book take the former view, and acquiesce in its corollary: "as in the past, so probably for a long time yet in the future, methods of treatment will appear that will have little sure basis in psychiatric theory, but which will justify themselves by their results." It is therefore regrettable that, appealing as they do to the arbitrament of results, the authors have not (except in the case of insulin treatment) given a full enough review of these results, published by various authors, to permit the reader to arrive at his own estimate of how valuable the methods are. The book is intended for the "young clinician in psychiatry, for the general practitioner, and the student," but even these might wish to be given, besides instructions and explanations, some material for judgment. Those, however, who wish only to be told how and when to use the various methods will find their needs fully supplied in this well-written manual.

The Nature and Treatment of Mental Disorder. By DOM THOMAS VENNER MOORE, O.S.B., Ph.D., M.D. Professor of Psychology and Psychiatry, Catholic University of America. William Heinemann, London. Pp. 312. Price 21s.

Many current textbooks of psychiatry give as much space to discussion and illustrative case histories as to straightforward exposition. Moreover the therapeutic precepts and professions in them, far from betraying the reputed dissensions among adherents of various schools, are so uniform from book to book that they seem almost to imply an orthodox canon which all but psychoanalysts acknowledge.

Professor Moore's book is the work of a Catholic priest, versed in scholastic and experimental psychology, and well known for his original, largely statistical approach to problems of nosology: yet it differs hardly at all in essentials from what may be found in any of the half-dozen textbooks of psychiatry lately issued from American and English presses. It differs, necessarily, in its treatment of some problems of conduct, arising often in psychiatric practice, on which the teaching of the Church is explicit; yet even here Dr. Moore does not take an inflexible standpoint in describing, for instance, how he treated a woman patient with phobias who had used mechanical contraceptives, he remarks that "an unsympathetic attitude towards her difficulties, a peremptory laying down of the law of the Church, however clear and logical, would have antagonized the patient and she would neither have conformed to the law of the Church nor have laid aside the phobia." The most interesting parts of this honest and urbane rather than profound book are the passages describing the psychiatric syndromes worked out by the tetrachoric method, and the sensible chapters on the methods of handling family problems.